PERFORMANCE EVALUATION OF DIFFERENT TYPES OF GRAPHITE ELECTRODES ON TITANIUM (Ti-6A1-4V)

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ABSTRACT

This thesis presents the EDMing of Titanium (Ti-6A1-4V) using POCO EDM 3 and POCO EDM C3 graphites electrodes with diameter of 10 mm. The main purpose of this study was to investigate the influenced of various parameters involved in EDM on the machining characteristics, namely, material removal rate (MRR), electrode wear ratio (EWR), surface roughness (Ra), recast layer (RL) and heat affected zone (HAZ) after undergone EDMing process and to compare the performance of both electrodes. The Full Factorial Design of Experiment (DOE) approach with two-level was used to formulate the experimental layout, to analyze the effect of each parameter such as pulse on (ON), pulse off (OFF), peak current (IP) and servo voltage (SV) on the machining characteristics EDM . In this investigation, the machining operation for titanium was performed using a Sodick linear motor EDM sinker series AQ55L. Meanwhile, for the measurement equipments; Mitutoyo Surftest SJ-400 was used to measure the surface roughness, and the thickness of recast layer and heat affected zone were examined using the Scanning Electron Microscope XL40. In general, results revealed that pulse on (ON) and peak current (IP) have appeared to be the most significant effect to all responses investigated. In term of performance, POCO C3 gives better material removal rate (MRR) value compare to POCO 3 but in term of electrode wear ratio (EWR) and also surface roughness (SR) POCO 3 gives better result compare to POCO C3. On the Recast layer and HAZ both the good and the worst came from POCO 3. The lowest recast layer achieved was 13.5 fxm and the lowest HAZ achieved was 12.7 Hm. Confirmation tests were also conducted for the optimum conditions for each machining characteristics in order to verify and compare the results from the theoretical prediction using Design Expert software and experimental confirmation tests. Overall, the results from the confirmation tests showed that the percentage of performance was acceptable due to all the results obtained were within the allowable values which was less than 15% of margin error.

ABSTRAK

Kajian yang dijalankan ini adalah mengenai pemesinan EDM *sinker* terhadap bahan Titanium (Ti-6A1-4V) dengan menggunakan *POCO EDM 3* dan *POCO EDM C3* yang berdiameter 10 mm sebagai elektrod. Tujuan utama kajian ini adalah untuk mengkaji kesan beberapa parameter yang terlibat dalam EDM proses terhadap kriteria pemesinan seperti kadar pembuangan bahan (MRR), nisbah kehausan elektrod (EWR), kekasaran permukaan (Ra), ketebalan lapisan tuangan semula (RL) dan zon kesan daripada haba (HAZ). Selain itu juga tujuan ujikaji ini juga untuk menyiasat keberkesanan elektrod *POCO EDM 3* dan *POCO EDM C3* serta membuat perbandingan prestasi elektrod tersebut. Rekabentuk ujikaji dengan pendekatan *Full Factorial* dua tahap ini digunakan bagi merekabentuk ujikaji, menganalisis kesan setiap parameter terhadap kriteria pemesinan seperti tempoh denyutan (ON), masa rehat (OFF), arus puncak (IP) dan voltan servo (SV). Dalam kajian ini, *Sodick linear motor EDM series AQ55L* digunakan. Sementara itu, bagi peralatan pengukuran; *Mitutoyo Surftest SJ-400* digunakan untuk mengukur kekasaran permukaan, dan akhir sekali, ketebalan lapisan tuangan semula dan kewujudan rekahan kecil diperiksa menggunakan *Scanning Electron Microscope XL40.* Keputusan menunjukkan arus puncak (IP) dan tempoh denyutan (ON) merupakan parameter yang paling signifikan terhadap kesemua respon yang dikaji. Manakala dari sudut prestasi, POCO EDM C3 memberikan kadar pembuangan bahan (MRR) yang lebih bagus jika dibandingkan dengan EDM*ing* menggunakan POCO EDM 3. Akan tetapi, POCO EDM 3 menunjukkan prestasi yang lebih baik daripada POCO EDM C3 dari segi kekasaran permukaan dan juga nisbah kehausan elektrod. Ujikaji pengesahan juga telah dijalankan bagi tujuan pengesahan dan perbandingan keputusan di antara nilai ramalan teori menggunakan perisian *Design Expert* dengan nilai yang diperolehi dari ujikaji. Secara keseluruhan, keputusan pengesahan ujikaji menunjukkan bahawa kesemua peratusan ralat perbezaan yang diperolehi berada di dalam lingkungan nilai yang dibenarkan iaitu peratus ralat kurang daripada 15%.

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LIST OF SYMBOLS

ANOVA	Analysis of variance
EDM	Electro discharge machining
EWR	Electrode wear rate
EWW	Weight of electrode used
HAZ	Heat affective zone
MRR	Material/metal removal rate
SEM	Scanning electron microscopy
SR	Surface Roughness
Wa	Weight of workpiece after machining
Wb	Weight of workpiece before machining
WRW	Weight of workpiece used
T64	Ti 6A1 4V
ON	Pulse On Time (Pulse Duration)
OFF	Pulse Off Time (Pulse Interval)
IP	Peak Current
SV	Servo Voltage
Ti	Titanium
A1	Aluminium

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Wire-EDM Process

Electrical discharge machining (EDM) is a non-traditional machining process developed to efficiently remove metal without mechanical forces. This new technology was developed primarily to machine extremely hard, high strength, tough, and temperature resistant materials and to produce complex-shaped parts. EDM is used when conventional machining method is either impractical or impossible. Also known as plunge, conventional, or ram, sinker EDM (Electrical Discharge Machining) generally uses a graphite electrode. The primary difference between sinker and wire is that it is used for applications such as blind shapes (George, T.,1999).

Sinker EDM, also known as conventional EDM, ram EDM, die sinker, vertical EDM, and plunge EDM is generally used to produce blind cavities. In sinker EDM sparks jump from the electrode to the workpiece. This causes material to be removed from the workpiece. During this process, the electrode never comes in contact with the workpiece. Prior to the EDM process, the electrode is machined as a reverse image of the cavity being created in the workpiece (Wang, C.C., and Yan, B.H., 2000).

Sinker EDM generates rapid electrical pulses between the electrode and workpiece. With sufficient voltage, a controlled spark precisely causes a small part of the workpiece to melt and vaporize. These pulses are repeated thousands of times per second. Each spark produces a temperature of approximately 10,000°C. The size of the spark penetration into the material depends on the energy turned out by the power supply.

Sinker EDM was primarily developed for the mold making industry (Figure 1.1). With the advancements in cutting speeds, reliability, unattended operation, and accuracy it is now being used in many other applications. Sinker EDM has offered a cost effective solution to previously difficult or impossible machining tasks. EDM applications are particularly suitable for production of parts that:

- Are difficult to machine because of toughness or hardness of material
- Have thin, intricate shapes or contours too difficult to machine by conventional techniques
- Contain odd-shaped cavities or holes

The increased use of EDM for production work has been due largely to improved machines, electrode materials, power supplies, improved techniques and research on EDM.

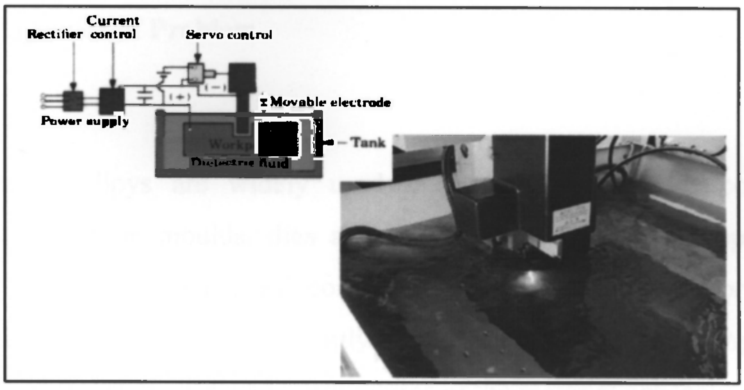

Figure 1.1: EDM die sinking process in Moldmaking Industries

In this study, the POCO EDM 3 (ultrafine graphite) and POCO EDM-C3 (graphite infiltrated with copper) electrode are applied to spark Titanium (Ti- 6Al-4V) workpiece. Graphite is widely accepted as an electrode material because it has high melting point and high temperature resistant. Graphite is easily to machine and available in various grades for application to all workpiece materials. Because the temperature at which graphite vaporizes is so much higher than any metal, the wear rates of graphite electrodes are extremely low.

The selection of EDM parameters is important in determining the accuracy and surface finish obtained for a particular application. For example when current is increased, each individual spark removes a larger crater of metal from the workpiece. Although the net effect is an increase in material removal rates, when holding all other parameters constant it also has the effect of increasing surface roughness. The same effect is also observed when spark voltage is raised. It is important to know very well and familiar with the parameter that control machining process before planning and designing machining process.

Therefore a study of the effects to machining characteristics such as electrode wear, material removal rate, crack formation and surface roughness and is of great significance and as the main objective for this research.

1.2 Background of Problem

Titanium alloys are widely used in various applications consisting of aerospace, automotive, moulds, dies and medical as a consequent upon its high strength to weight ratio and good corrosion resistance. Ti-6A1-4V or commonly known as "T64" is one of most frequently titanium alloys used in varying industries. It is understood that the metallurgical structures of the material consequent its lack of conductivity characteristics and it is categorized as difficult to machine material emphasizing on conventional machining processes. (Hascalic, A., and Caydas, U., 2007). EDM does not make direct contact between the electrode and the workpiece where it can eliminate mechanical stresses chatter and vibration problems during machining. Materials of any hardness can be cut as long as the material can conduct electricity (Hascalic, A., and Caydas, U., 2007). Hence, titanium, which is difficult-to-cut material, can be machined effectively by EDM (Wang, C.C., and Yan, B.H., **2000).**

Graphite has been predominant material for EDM electrode. Graphite electrodes are commonly used in application requiring little tool wear and high material removal rate. It is normally used for machining steel. It is normally provide high metal removal rates per ampere as compared with metallic electrodes materials. It is also an advantage for graphite for being easy to machine either by grinding, milling, turning or boring. However there are certain limitations when using graphite electrode to machine titanium.

For the past years, there are tremendous researches and developments being carried out to develop a new type of graphite with improve features. One of them is mixing copper into graphite which is known as .copper- graphite. This new type of electrode can contribute to a better result in machining titanium as other electrode failed to do so. It can be said that the performance these new graphite are much better compare to past or previous graphite.

Although much work has been done in EDM of materials, optimization EDM condition, machining characteristic of EDM of titanium alloy in relation to machining parameters and different electrode materials is rather lacking. The aim of this study is fulfilling a detailed investigation of electrical discharge machining characteristic of Ti-6A1-4V in relation to process parameters and different electrode materials.

1.3 Problem of Statement

a. Does the performance of POCO EDM-C3 gives better results in terms of, Material Removal Rate, Surface Roughness, Electrode Wear Rate and Surface Integrity of titanium alloys (Ti-6A1-4V) compared to POCO EDM 3.
b. Does POCO EDM-C3 (graphite infiltrated with copper) gives better option in machining titanium compared to POCO EDM 3 that been used widely from the past couple of years.

1.4 Thesis Objectives

The objectives of this project were as follows:

a. To study the Machinability of Ti- 6A1- 4V using POCO 3 and POCO C3 during the EDM process.
b. To evaluate the effect of machining parameters on the Material Removal Rate (MRR), Electrode Wear Ratio (EWR) and Surface Roughness (SR).

To investigate the Recast Layer and Heat Affected Zone (HAZ) on the machined surface.

To compare both electrodes in terms of their result on all 3 responses.

Thesis Scopes

The studies were limited to the following scopes:

Sodick AQ55C EDM die sinking machine was used to run the experiment with different predetermined parameters.

POCO EDM 3 (ultrafine graphite) and POCO EDM-C3 (copper infiltrated graphite) was used as the electrodes.

Kerosene was used as the dielectric medium.

The machining responses that will be investigated are Material Removal Rate (MRR), Surface Roughness (SR), and Electrode Wear Rate (EWR).

Analysis on the Recast Layer (RL) and Heat affected Zone (HAZ) only being conducted on selected sample.

Full Factorial Experimental Design (DOE) will be employed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Non conventional machining has become a one of the most popular area of interest among researcher due to the various advantageous offered by this process. One of the most widely and famous type of non conventional machining processes is Electrical Discharge machining (EDM). This type of machining is used for machining difficult to machine materials like super alloys and titanium alloys (Hascalic, A., and Caydas, U., 2007). Good electrical conductivity is a requirement for the fast machining of any material by EDM process.

From the past experiences, it showed that EDMing of titanium alloys is quite complicated as compared to other material due to the material properties of the former alloys (Asokan, T., *et. al,* 2000). Its low electrical conductivity, make it difficult to machine by EDM process. No standard technologies are readily available for setting the cutting parameters such as current, polarity, duty cycle, etc, to achieve the desire machining characteristics of the titanium alloys in particular Ti-6A1-4V.

2.2 Research trend for EDM

In the past decade, there are a lot of research have been carried out around the world by the various individual to investigate things that related to improving performance measures, optimizing the process variables, monitoring and control the sparking process, simplifying the electrode design and manufacture in EDM die sinking process. Some of them have explored a number of ways to improve the sparking efficiency including some unique experimental concepts that depart from the EDM traditional sparking phenomenon. Although there a various area that been investigated, but still this new research shares the same objectives which is achieving more efficient metal removal coupled with a reduction in tool wear and improved surface quality. This is to help the EDM user to be satisfied on choosing this type of machining process to produce their part. Some of the main areas that popular among the researcher are as below.

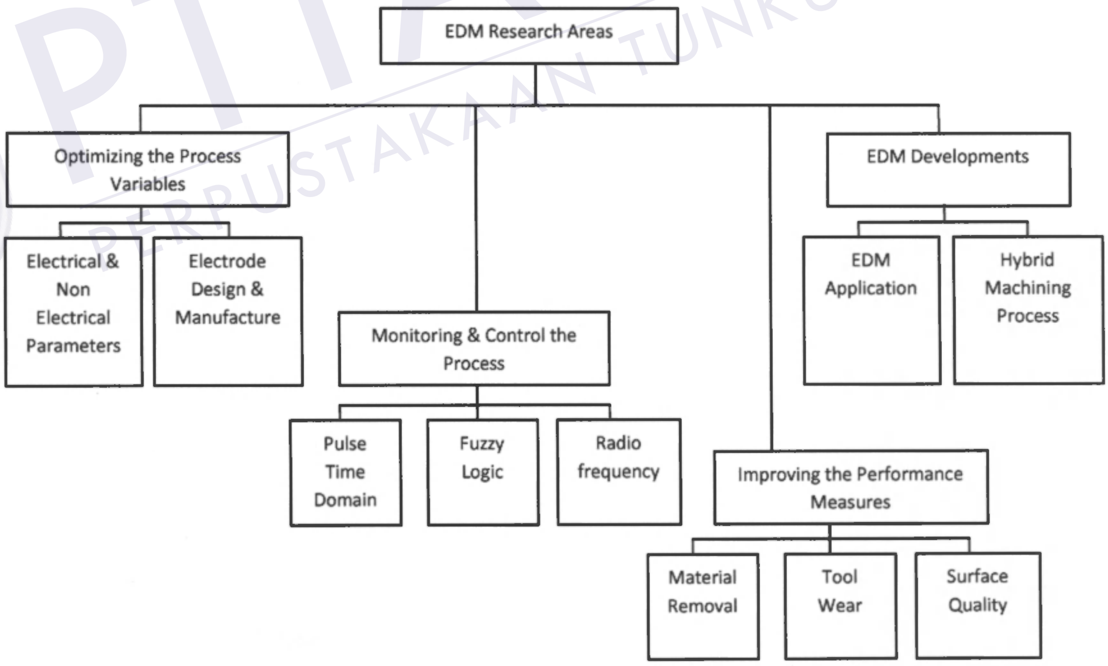

Figure 2.1: The most popular research areas in EDM

2.3 Electric Discharge Machining (EDM)

Electrical discharge machining, generally referred to as EDM, is a process used to remove metal from any material, hard or soft, that conducts electricity. The dc power supply provides the energy for electrical discharges between the electrode and workpiece. The power supply is designed to control the amount of energy and the number of discharges per second. These discharges are actually intermittent sparks from the electrode (cutting tool) that erode the metal away from the workpiece. The cavity thus produced conforms to the shape of the electrode. During the EDM process, the cutting tool and the workpiece must never touch each other. If this should happen there would be an electrical short circuit and no metal removal would take place. Figure 2.2 at below shows basic components of an EDM (Sommer, C., 2000).

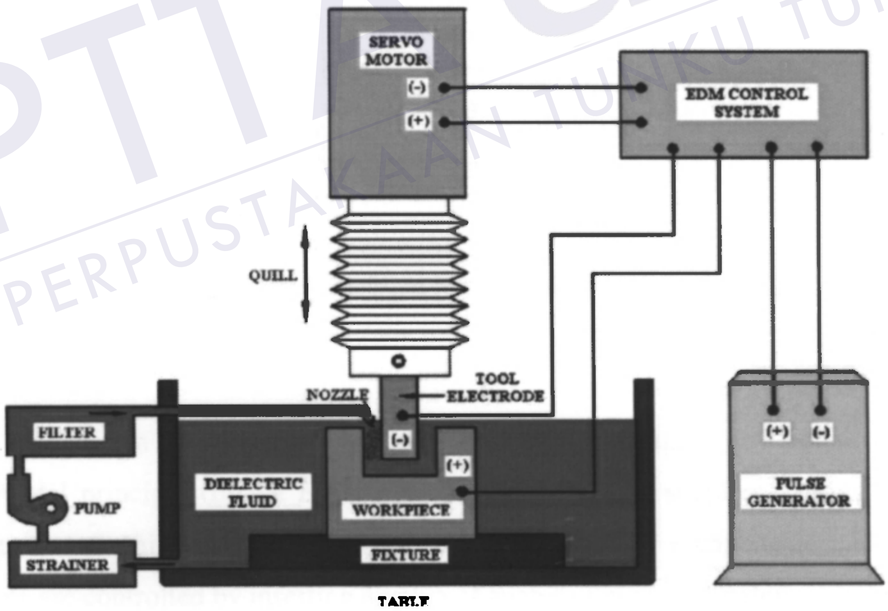

Figure 2.2: Schematic diagram of Sink EDM process

EDM has been an important manufacturing process not only for the tooling, mould and die industries but also for aerospace industries for several decades. The process is finding an increasing industrial use due to the ability of producing geometrically complex shapes as well as its ability to machine hard materials that are extremely difficult to machine when using conventional process. EDM can be categorized into two: die sink EDM and wire EDM (Sommer, C., 2000). However, EDM processes also can be classified into three main categories as shown in below (Pandey, P.C., and Shah, H.S., 1980).

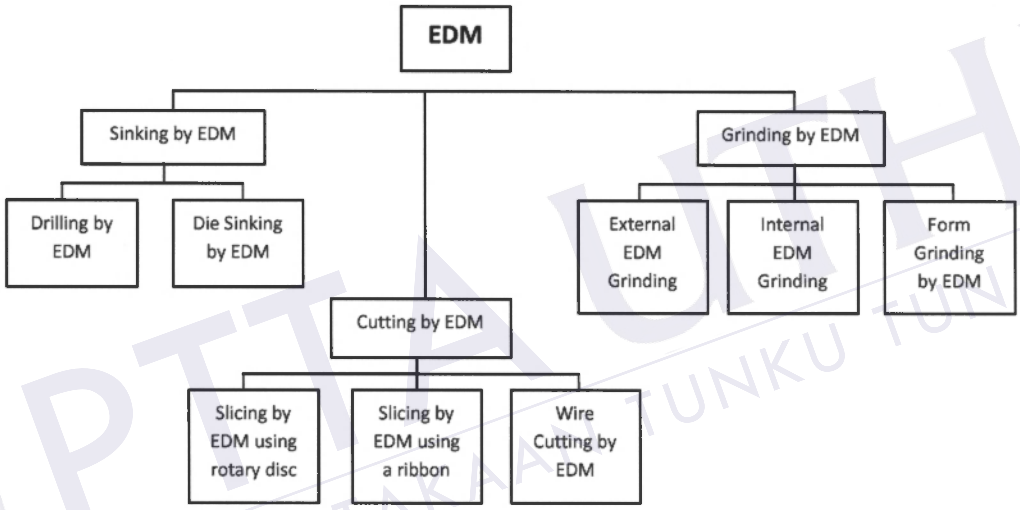

Figure 2.3: Classification of EDM processes

Application of the EDM process requires thorough knowledge of the fundamental principles of the EDM machine, EDM power supplies, cutting tools, coolant, and flushing techniques. Basically, all these four components and their functions are controlled by inserting a value of such common parameters of EDM for instance; machining voltage, peak current, pulse duration (on-time), interval time (off-time) and other parameters. Generally, EDM parameters are categorized into two-groups which are electrical and non-electrical parameters. The electric parameters comprise of polarity, peak-current, pulse duration and power supply voltage. The non-electrical parameters include circumferential speed of electrode, reciprocating speed and flushing. Below is the figure that shows the main component of the EDM system.

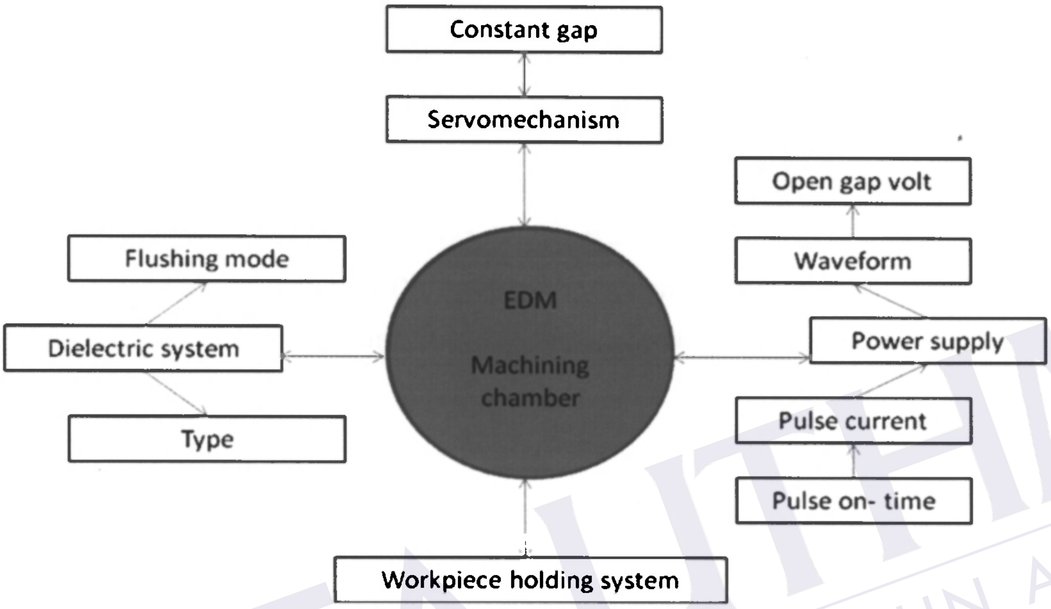

Figure 2.4: Main component of the EDM system

2.3.1 Machining Parameters

The machining performances depend on various EDM parameters (variables). The parameters can be categorized into two different groups which are electrical and non electrical parameters. In electrical parameters it comprise the polarity, peak current, pulse duration and power supply voltage meanwhile for the non electrical parameters it comprise the rotational of speed electrode and also the injection flushing pressure (Wang, C.C., and Yan, B.H., 2000).

There are some researchers that have categorized the parameter in different ways which is into 5 groups which is dielectric fluid, machine characteristic, tool, workpiece and adjustable parameters (Hascalic, A., and Caydas, U., 2007). However adjustable parameters which comprise discharge current, gap voltage, pulse duration, polarity, charge frequency, capacitance and tool materials are always considered as critical parameters (Wang.C.C., and Yan, B.H, 2000), (Singh, U.P. et.al 1985), (Tzeng, Y.F., and Chen, F.C., 2003).

But there are also researches that have been done on the non electrical parameters such as on the dielectric flushing. It has been found out that it affect the EDM performance due to the changing of erosion rate, mirror like finishing achieved .by multi divided electrode method (Mohri, N. et.al., 1996). It also have been found that Improved jet flushing for EDM lead to distribution phenomenon of debris had a good correlation with the geometry of the workpiece surface produced (Masuzawa, T., et.al., 1992).

2.3.2 Electrode Materials

The selection of the most appropriate sinker EDM electrode material is a key decision in the process pan for any sinker EDM job. The electrode in die sinking EDM is formed to the shape of the cavity desired. As in conventional machining, some materials have better cutting and wearing qualities than others. Electrode materials must, therefore, have the following characteristics:

1. Be good conductors of electricity and heat
2. Be easily machined to shape at a reasonable cost
3. Produce efficient metal removal from the workpiece
4. Resist deformation during the erosion process
5. Exhibit low electrode (tool) wear rates

Much experimentation has been carried out to find a good, economical material for the manufacture of EDM electrodes. The more common electrode materials are graphite, copper, copper graphite, copper tungsten, brass, and steel. None of these electrode materials has general purpose application; each machining operation dictates the selection of the electrode material. Yellow brass has been used primarily as electrode material for pulse-type circuits because of its good machinability, electrical conductivity, and relatively low cost. Copper produces better results in the resistance-capacitance circuits where higher voltages are employed (Ahmet, H. and Caydas, U., 2007). (Naveen, B., *et.al.*, 2008). Electrode material properties are showed in Table 2.1.

Table 2.1: Properties of graphite and copper electrode

MATERIAL	GRAPHITE	COPPER
Composition	99.9% Graphite	99.9 % Copper
Density (g/ cm^3)	1.811	8.904
Melting Point (°C)	3350	1083
Electrical resistivity (μΩ cm)	1400	9
Hardness	HB 10	HB 100

The normal copper that is used as electrode is either pure copper or an electrolytic-grade copper. Copper is most used when the smoothest surface finishes are required. Limited wear also can be achieved by using copper electrode but it requires extremely low dielectric pressure. Copper electrodes have been used primarily in resistance capacitance circuits where higher voltages are employed. These electrodes also offer good size control (Mahajan, V.K., 1981). Graphite has been predominant material for EDM electrode. Graphite electrodes are commonly used in application requiring little tool wear and high material removal rate. It is normally used for machining steel. It is normally provide high metal removal rates per ampere as compared with metallic electrodes materials. It is also an advantage for graphite for being easy to machine either by grinding, milling, turning or boring (Kalpakjian. 1995).

2.3.2.1 Graphite electrode

Graphite is the preferred electrode material for 90% of all sinker EDM applications. Thus, it is important that we expend considerable effort to understand its properties and application to EDM. Graphite was introduced to the EDM industry approximately 50 years ago. One of the early well known brands of graphite was manufactured by General Electric, and known by the trade name of "Gentrode". Graphite is made from Carbon derived from petroleum.

The powdered Carbon is mixed with a petroleum based binder material and then compacted. How the graphite is compacted in this stage of production is vitally important to its ultimate properties. All early graphites were made by compressing the powder/binder mixture in only one direction, resulting in properties or "grain" similar to wood, that varied relative to the direction of pressing. As an outgrowth of the space program, methods were developed to isostatically press graphite such that its properties became "isotropic", that is the same in all directions. All high quality, high performance graphites are now manufactured this way. After compacting, the "green" compacted material undergoes a series of thermal treatments that convert the carbon to graphite.

Graphite has certain properties quite different than wrought metal based electrode materials:

- Graphite has an extremely high melting point. Actually, graphite does not melt at all, but sublimes directly from a solid to a gas (just as the Carbon Dioxide in dry ice) at a temperature thousands of degrees higher than the melting point of Copper. This resistance to temperature makes graphite an ideal electrode material.

  Graphite has significantly lower mechanical strength properties than metallic electrode materials. It is neither as hard, as strong, nor as stiff as metallic electrode materials; however, since the EDM process is one of relatively low are macro mechanical forces, these property differences not often significant.

Due to the significant differences between metallic electrodes and graphite, there are certain properties, unique to graphite that are commonly specified and controlled:

- **Particle Size** - Generally, the smaller the particle size, the better the mechanical properties of the graphite, which result in finer detail, better wear, and better workpiece surface finish.

- **Density** - Since graphite is a porous material, density must be closely controlled. Generally, higher density is preferable.

- **Flexural Strength** - Flexural strength is a measure of the strength of the graphite. Generally, graphite with the smallest particle size has the highest flexural strength.

- **Hardness** - Hardness is often a function of the particle size, porosity, and binder material. Hardness can be very important to the success of machining and grinding operations.

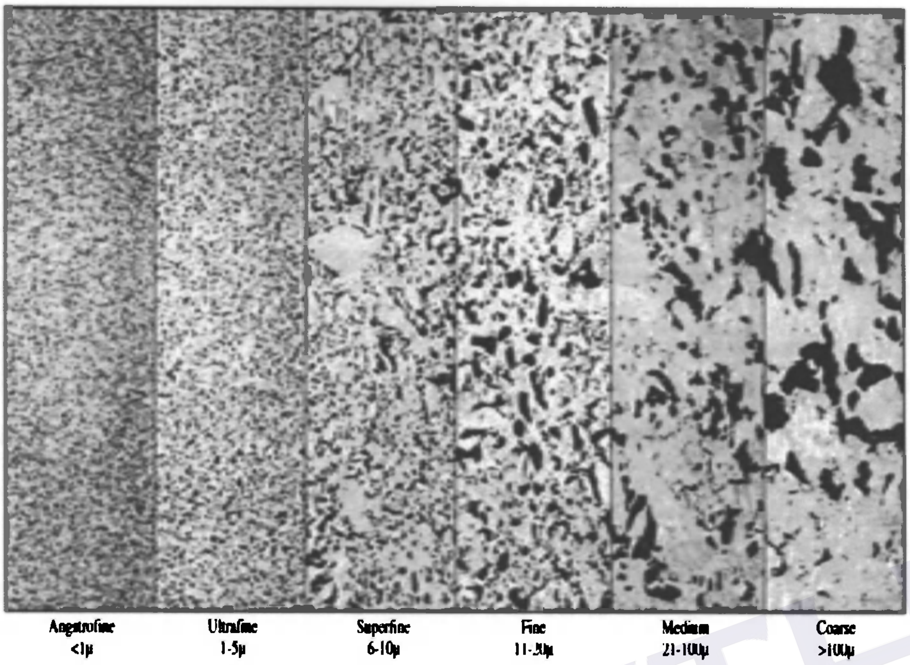

Figure 2.5: The different grades and porosities of graphite electrode

Graphite is widely used due to its significant production advantages over metallic electrode materials:

- **Speed** - Graphite is faster than Copper in both roughing and finishing, usually by a factor of 2:1.

- **Wear** - Graphite usually wears less than Copper.

- **Surface Finish** - With advances in dielectric, power supply electronics, and orbiting, achievable graphite finishes match those formerly only attainable with Copper.

- **Machinability** - Graphite machines and grinds an order of magnitude faster than Copper, and can also have more detail easily machined into it. Graphite doesn't have to be de-burred like any metallic does, further reducing electrode fabrication costs.

2.3.2.2 Graphite infiltrated with copper electrode

Copper graphite is graphite manufactured with a controlled amount of interconnected porosity which is then infiltrated with Copper by capillary action in a furnace. The resulting material has increased electrical conductivity and mechanical strength. Copper graphite offers the combined benefits of the ease of fabrication of graphite, and the burn stability and "safety" of Copper. Copper graphite has shown particular advantage when applied to aerospace applications such as Titanium, Inconel, and other high temperature aerospace alloys. Copper graphite is also applied to the EDMing of carbide. Copper graphite electrodes are not nearly as fragile as graphite electrodes; however copper graphite suffers from increased corner wear when compared to the same non-impregnated grade.

2.3.3 Flushing Methods

Flushing is the most important requirement of a dielectric fluid. Inadequate flushing can result in arcing, decreased electrode life, and increased production time. The fluid should have the ability to flow through the spark gap, removing debris, chips, and particles eroded by the EDM process. Improper flushing causes erratic cutting thus prevents the electrode from cutting efficiently. It is then necessary to remove the attached particles by cleaning the workpiece. Dielectric fluid is used as flushing to assist in the removal process of particles from the work area hence giving better surface finish (Wong, Y.S., et.al., 1995). There are five types of flushing fluid system in EDM (Sommer, C., 2000).

1. Pressure flushing
    a. Through electrode
    b. Through workpiece
2. Suction flushing
3. Combined pressure and suction flushing
4. Jet flushing

5. Pulse flushing
    a. Vertical flushing
    b. Rotary flushing
    c. Orbiting Flushing

There is effort to improve the EDM efficiency by supplying gas into the gap and they found that the stock removal rate is increased (Kuneida, S. and Furuoya, S., 1991). There is also a report that by improving the jet flushing, it indirectly improves or increase the effectiveness of EDM (Masuzawa, T., *et.al.,* 1992)

2.3.4 Dielectric Fluid

Dielectric fluid is a very important part of the sinker EDM process. It serves as a flushing agent to clear the cut zone of loose debris. . The fluid forms a dielectric barrier for the spark between the workpiece and the electrode. Equally important, the dielectric acts as an insulating media between the electrode and workpiece. Basic characteristics required for dielectric used in EDM are high dielectric strength and quick recovery after breakdown (Wong, Y.S., *et.al.,* 1995). The two main differences amongst most fluids is the stability of the erosion process and the effects on the operator's skin.

Since different dielectric have different cooling rates and compositions, the choice of dielectric plays an important role in the EDM process. Most dielectric media are hydrocarbon compounds and water. The hydrocarbon compounds are in the form of refined oil; better known as kerosene. While the fluid properties are essential, the correct fluid circulating methodology is also important. The selection of suitable dielectric is based on the type of materials and the processes that are used. The performance of the dielectric may vary from one workpiece to another. During the investigation of EDM of Ti 6A1 4V, they found that the MRR was greater and the relative EWR is lower, when using distilled water as dielectric solution (Chen, S.L., *et.al.,* 1999). There are also experiments that try to use gas as dielectric media, and they found that tool EWR was almost zero for any pulse duration (Kuneida, S. and Furuoya, S., 1991).

2.4 EDM Machining Characteristics

2.4.1 Microcracks

The microcracks produced by EDM are the result of thermal stresses created during the on-time phase of the EDM cycle. The depth of the microcracking is partially controlled by the EDM program and it goes without saying that as the spark intensity increases so does the depth of the white layer. This also facilitates an increase in the number and size of microcracks present in the cavity. Obviously, the surface integrity affected by the EDM process can be controlled by the technologies of today's EDM power supply. The specific parameters that affect the surface integrity are voltage, amperage, on-time and duty cycle. These parameters can be manipulated to optimize efficiencies and control surface integrity in the roughing, semi-finishing and finishing stages.

Since the EDM discharge produces the white layer and micro-cracking, it is safe to say that the depth will be as thick (or as thin) as the intensity of the spark energy. As the spark energy is reduced, such as we see in changing from a roughing condition to a finishing condition, the depth of the white layer and appropriately enough, the cracking also will be reduced.

During machining, the discharge energy produces very high temperatures at the point of the spark on the surface of the workpiece and removes the material by melting and vaporization. The top surface of workpiece resolidified and cool subsequently at very high rate. This process leads to the slightly dimpled surface such increasing surface roughness, which facilitates crack initiation on the surface. After electrical discharge treatment, high tensile residual stresses often induce damage such microcracks or pinholes in the surface layer, reducing the strength (Kuneida, S. and Furuoya, S., 1991) (Chen, S.L., *et.al.*, 1999) (Ahmet, H. and Caydas, U., 2007) (Lin, Y.C., *et.al.*, 2000).

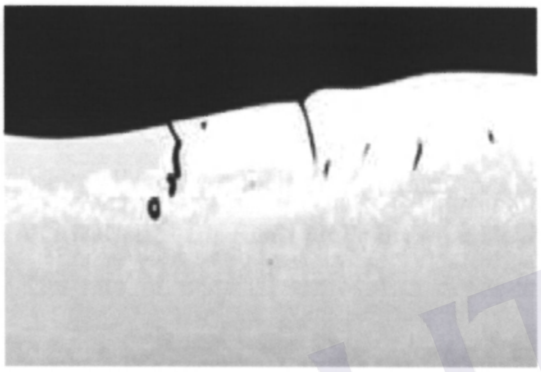

Figure 2.6: Cross section illustrating microcracks in the white layer (Complete EDM Handbook)

2.4.2 Electrode Wear Ratio, EWR

Electrode wear rate is weight difference of the electrode before and after machining. Electrode wear depends on a number of factors associated with the EDM like voltage, current, electrode material and polarity. During the discharge process, the electrode as well as the workpiece, is subject to wear or erosion. As a result, it is difficult to hold close tolerances as the tool gradually loses its shape during the machining operation. At times it is necessary to use as many as five electrodes to produce a cavity of the required shape and tolerance. With graphite electrodes, this wear ratio can be greatly improved 10:1. Much research and development remains to be done to reduce the wear ratio of the electrode. Reverse-polarity machining, a relatively new development, promises to be a major breakthrough in reducing electrode wear. With this method, molten metal from the workpiece is deposited on graphite electrode about as the electrode is worn away. Thus minute reverse-polarity machining operates best on low spark-discharge frequencies and high amperage. It improves the metal-removal rates and greatly reduces electrode wear (Ahmet, H. and Caydas, U., 2007) (Singh, U.P *et.al.,* 1985) (Naveen, Bari., *et.al.,* 2008) (Wong, Y.S., *et.al.,* 1995).

2.4.3 Material Removal Rates, MRR

The material; removal rate is a measure, defining removed material volume per minute. Material removal rates for EDM are somewhat slower than conventional machining methods. The rate of material removal is dependent on the following factors:

- Amount of current in each discharge
- Frequency of the discharge
- Electrode material
- Workpiece material
- Dielectric flushing conditions

As the current increases, metal-removal rate increase. A spark of 1 ampere (A) erodes a certain amount of metal. When the current is doubled, the energy in the discharge is also doubled and approximately twice the amount of metal is removed. In has been proved by one of the research that carried out experiment using graphite electrode on titanium workpiece. It shows that the material removal rate also increase with the pulse on duration. Form the research also it is found that the material removal rate of graphite electrode is highest compare to copper and aluminum (Ahmet, H. and Caydas, U., 2007).

2.4.4 Surface roughness, Ra

The surface finish is controlled by the number of discharges per second, more often referred to as the frequency sparks. The greater amount of energy applied the greater amount of material removed. However, when greater amounts of current are used, larger craters are eroded from the work, causing a rougher surface finish. To maintain increased metal-removal rates and at the same time improve the surface finish, it is necessary to increase the frequency of the discharges. Surface integrity involves the measures of surface roughness, heat affected zone, micro hardness, micro crack, residual stress, diffusion of tool material and carbon and endurance limit. For this thesis only surface roughness and surface hardness will be investigated because of inadequacy of specialized equipment (Machado, R., and Wallbank, J., 1990).

2.5 Titanium materials and its Alloys

Titanium alloys are available in four varieties: alpha, alpha/ beta, beta and the newer titanium aluminide. Because more alloying elements are being added to the particular grades, these alloys are progressively more difficult to machine. The Alpha phase of titanium is pure titanium, relatively soft and can be machined at high speeds. This material presents no significant machining problems. However, the material lacks the beneficial properties of the other alloys, primarily strength and flexibility, so its uses are limited.

Alpha/beta alloys are the most common titanium alloys, and Ti-6A1-4V (6% aluminum, 4% vanadium) is used extensively in the aerospace industry, particularly for jet engines. Ti-6A-4V is used to a lesser extent in the medical and chemical industries. These alloys are moderately difficult to machine, and relatively short tool life can be a problem because alpha/beta chips are difficult to break and are abrasive.

Beta phase titanium alloys do not have the toughness of the alpha/betas, but they are harder and more brittle. They also are more difficult to machine because of the higher percentages of vanadium, molybdenum and chromium with which they are made. Beta phase alloys of titanium are becoming more common, and present serious machining challenges.

Titanium aluminides are very difficult to machine, but they are extremely lightweight and strong. Earlier, a lack of toughness limited their application. However, material science research has addressed their lack of toughness, and applications are beginning to be developed in auto racing engines, where they are used for push rods and valve stems, and in components for jet engines (Naveen, Bari., *et.al.,* 2008).

2.6 Critical Review on EDMing of Titanium Alloys

2.6.1 Introduction

Titanium is present in the earth's crust at a level about 0.6% and is therefore the fourth most abundant structural metal after aluminum, iron, and magnesium. The first suspicion of a new, unknown element present in a dark, magnetic iron sand was expressed in 1791 by Gregor and in 1795, Klaproth found the same thing. Klaproth named the element titanium after the Titans, mythological Greek gods (Kalpakjian., 1995). Although it has been around for over two hundred years, it has only been produced commercially since 1950's. High strength, low density, and excellent corrosion resistance are the main properties that make titanium attractive for a variety of applications.

Titanium and its alloys provide excellent corrosion resistance, a high strength to weight ratio and good high temperature properties. Ti6AI4V, a titanium alloy commonly known as T64, is commonly used for space and aircraft applications, as well as high performance automotive and marine applications that require materials with high corrosion resistance and strength. Titanium and its alloys are classified as difficult to machine materials by conventional machining processes. The main difficulties in machining them are high cutting temperatures and rapid tool wear. Therefore, for machining of these materials, unconventional machining processes are recommended.

The major application of the material is in the aerospace industry, both in airframes and engine components. Non aerospace applications take advantage mainly of their excellent strength properties, for example steam turbine blades, superconductors, missiles etc,; or corrosion resistance, for example marine services, chemical, petrochemical, electronics industry, biomedical instruments etc. Titanium is expensive when compared to many other metals, because of the complexity of the extraction process, difficulty of melting and problems during fabrication. The machinability of titanium and its alloys is generally to be poor owing to several inherent properties of the materials (Machado, R., and Wallbank, J., 1990).

2.6.2 Machining Titanium Alloys with EDM

The machinability of titanium and its alloys is generally considered to be poor owing to several inherent properties of the materials. Titanium is very chemically reactive and, therefore, has a tendency to weld to the cutting tool during machining, thus leading to chipping and premature tool failure. Its low thermal conductivity increases the temperature at the tool and workpiece interface, which affects the tool life adversely. One of the researcher pointed that EDM of titanium

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