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A

THESIS

Presented to the faculty of

The University of Texas Graduate School of Biomedical Sciences

at San Antonio

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

By

Guillermo E. Orraca, D.M.D.

San Antonio, Texas

May, 1997

EROSION RATE, SURFACE FINISH AND ELECTRODE WEAR IN ELECTRIC DISCHARGE MACHINING (EDM) OF DENTAL ALLOYS

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Supervising Professor

April 14, 1997
Date

APPROVED:

Sanford A Miller, Ph.D.
Professor and Dean

DEDICATION

This thesis and the effort it represents, is dedicated to all those whom I love and hold dearly in life.

My parents Guillermo E. Orraca and Laddie L. Orraca have encouraged and inspired me to always do my best. They have provided emotional support for so many years. Also thank them for their tireless efforts that made things in my life possible.

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ERROSION RATE, SURFACE FINISH AND ELECTRODE WEAR IN ELECTRIC DISCHARGE MACHINING (EDM) OF DENTAL ALLOYS

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Supervising Professor: Barry K. Norling, Ph.D.

A precise fit of dental restorations is critical in all aspects of prosthetic dentistry. Fabrication of a prosthesis with a high degree of accuracy is difficult due to the dimensional changes of different dental materials. EDM is an extremely accurate non-contact machining process with a precision as small as 0.002 mm. The objectives of this study were to investigate how changes in amperage and on-time of the EDM process affect the metal removal rate (MRR) and surface finish (R_a) of representative dental materials. The percentage of electrode wear (PEW) of representative electrode materials in different metal-electrode combinations was also studied. Three representative dental metals (workpieces) were used; Type III gold (Ney), Olympia ceramo-metal Alloy (Jelenko) and titanium (Ti) (Rematitan). Type III gold and ceramo-

metal alloy were cast in bars 6mm square and 30 mm in length. Ti ingots were used as provided by manufacturer. Three different electrode materials were used; graphite (AF-5), copper-graphite (C-3) and copper (Cu). All electrodes were 4.7 mm. diameter with a flushing hole of 0.5 mm. On times were 4.0, 25.6, 51.2 μseconds and currents were 0.468, 0.936, 1.872 Amperes. Triplicate measurements of MRR, electrode wear, and R_a were made. Factorial analysis was applied to give statistical evaluation for MRR, surface finish and PEW. The analysis included the comparisons of different levels of amperage and on-time together with the test of statistical significance. Separate analysis were made for each metal-electrode combination. A four-way ANOVA on electrode wear, metal removal rate and surface finish showed significant effects of metals, electrode material, amperage and on-time. The interaction of these factors were also highly significant. Significance level was the conventional five percent ($p \leq 0.05$). When considering changes in amperage, the results of this investigation showed that as amperage increased MRR and R_a values increased regardless of metal-electrode combination, polarity or on-time. Better surface finishes (lower R_a values) were produced at lower amperages (0.468 A) However changes in amperage did not consistently affected the electrode wear. Titanium was an exception to the others alloys, negative polarity at lower amperage produced more PEW than higher amperage. When changing on-time the results showed that the on-time significantly affect the MRR and the electrode wear of the different electrode-metal-polarity combinations when the amperage and all other variables remains unchanged. MRR's were highest for on-times of 25.6 μSec. and lowest for 4.0 μSec. on-times, with the exception of the titanium/AF-5 (+) polarity and the titanium/C-3 (-) polarity combinations where MRR's were higher for 4.0 μSec. and lower for 51.2 μSec. on times. Higher on-times 25.6 and 51.2 μSec significantly reduced the electrode wear. Better overall performances were produced with the following metal-electrode combinations; gold-copper. Olympia-AF-5, Olympia-copper, Titanium (+) polarity-copper and Titanium (-) polarity-AF-5. MRR's as high as 481.97 mm^3/hr., R_a values as low as 0.57 μm and electrode wear as low as 0% was obtained in this investigation.

EDM has been used for over 50 years to machine metals and make precise molds. The fitting is very precise and any material that conducts electricity can be machined. This investigation established initial machining parameters for the use of EDM with representatives dental alloys. Future dental applications of EDM are promising not only in the correction of casting inaccuracies but as a useful tool for dental device manufacturing.

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I. INTRODUCTION

Several methods have been proposed to correct inaccuracies resulting from dental casting procedures. When dealing with natural teeth, microscopic movements within the periodontium help to compensate for some of these inaccuracies. Because osseointegrated implants lack periodontal ligaments and are solidly attached to bone, cast metal superstructures must be fabricated to accurately attach to the implant abutment. If superstructures do not fit passively, numerous post-operative complications may occur. Fractures involving implants or prosthetic components, and loss of osseointegration have been attributed to non-passive fit. The most common method to correct non-passive fit involves sectioning a framework, correcting the relationship, and soldering at the corrected position. Soldering, however can be time consuming, is not always accurate, can change the physical properties of the metal, and in some cases results in less than satisfactory adaptation. Methods employing luting agents solve this problem but are not very durable, and contours may be affected affecting prosthesis longevity. One of the most promising techniques to improve passive fit is electric discharge machining (EDM).

Electric Discharge Machining is a process that utilizes electrical discharges, or sparks, to machine any electrically conductive material. High energy sparks erode the material by vaporization, melting, and the explosive effect of dislodging a minute particle of metal from the workpiece which leaves a small crater. The expelled particle is then washed away by a circulating dielectric oil. The EDM cycle can be repeated up to 250,000 times per second, depending on the duration and intensity of the electrical pulses.

Electric discharge machining has been used in industry for more than 40 years. The first documented use of the EDM process in dentistry was reported in 1982. EDM was used for the addition of friction pins and extracoronal extensions in fixed and removable prostheses. Other uses of EDM in the dental literature include machining precision attachments for fixed, removable and implant prostheses, fabrication of components for implant prostheses, correction of casting inaccuracies and fabrication of unalloyed titanium restorations.

Some of the advantages of the EDM process are: 1) The workpiece may be fabricated from any material as long as it is electrically conductive. 2) EDM is not controlled by metal hardness since it is a non-contact process. 3) EDM is extremely accurate with precision in the order of 0.002 mm. 4) Objects can be machined without distortion, because there is no contact between the electrode and the workpiece.

EDM is best described as a thermoelectric process in which heat and electricity work together. Both electrical flow (amperage) and cyclical application of on and off impulses, produce this thermoelectric energy that melts, vaporizes and ejects material from the workpiece. Pulses are defined in terms of "on-time" and "off-time". The amperage and "on-time" are the principal factors regulating metal removal rate. Surface finish and electrode wear also are controlled by these factors.

Electrode wear is a very important parameter. The higher the electrode wear, the greater the inaccuracy of the resulting end product. It is possible to establish a cut in which the wear of the electrode is kept to a minimum with a technique known as the "no-wear" mode. The "no-wear" mode can be accomplished by producing a long on-time and carefully controlling the amperage.

Metal-electrode combination and various physical properties such as conductivity, melting point, resistivity and particle size directly influence the metal removal rate, surface finish, and electrode wear of the EDM process.

All these factors directly affect the quality and performance of the EDM process. However, there is no documented study available regarding optimum parameters recommended to machine dental alloys using the EDM process. This study investigated several parameters used in the EDM process with the objective of determining the optimum parameters for machining representative dental alloys. By determining these parameters, the use of EDM in dental applications will be enhanced, resulting in efficient, highly precise, consistent and accurate machining techniques.

II. LITERATURE REVIEW

A. Historical Events of Pre-Implant Dentistry

Practicing dentists spend much of their time replacing partially or completely missing tooth structure. Different techniques have been developed and used over the years to replace missing teeth. However, researchers continued to search for improved methods of anchoring prosthetic materials within the jaw to reconstruct an entire tooth either as a single restoration or as support for a complete denture, removable partial denture, or fixed partial denture. The main goal is to achieve a dental appliance or prosthesis that is not only aesthetically acceptable, but functions like the original dentition. To most people, tooth loss provides a strong incentive to seek professional care for preservation and restoration of masticatory function, normal speech, and socially acceptable appearance.

The desire to provide a substitute for a single tooth or an entire arch began in ancient civilizations, where gold and ivory were common prosthetic materials. According to Weinberger (1947) and Ring (1985), by 500 BC the Egyptians carved ivory teeth and attached them with gold wire to adjacent natural teeth. There is also evidence that by 400 BC, if not earlier, the Etruscans fabricated perfectly fitted gold bridges, which required knowledge, not only of the technology of metal working, but of gold soldering as well. The Romans improved the practice of prosthetic dentistry by inventing gold shell crowns and constructing artificial teeth from bone, boxwood, and ivory.

Ring (1985), stated that the recorded history of implant dentistry goes back to about 600 AD, when it was practiced by the Mayans in the region of Honduras. In 1931, while excavating in the Ulva Valley of Honduras, Dr. and Mrs. Popenoe found a mandible fragment of Mayan origin that had three tooth shaped pieces of shell in the sockets of three missing mandibular incisors. In 1970, Dr. Bobbio of Brazil examined these shell implants with x-rays and found compact bone around two of them that was radiographically similar to bone that forms around blade implants. These are the earliest endosseous alloplastic implants known to have been placed in a living person.

In the 16th century, Ambrose Pare (1510-1590), introduced the first maxillary obturator for cleft palate habilitation, the ligation of arteries, and the replantation and transplantation of teeth as an alternative method for replacing missing teeth. According to Ring (1985) and Carter (1987), during the 17th to the 19th centuries transplantation of teeth became a very popular procedure. Pierre Fauchard (1678-1761) worked on replantation techniques of avulsed teeth and transplanted teeth from one person to another. John Hunter (1728-1793) established guidelines for tooth transplantation. According to Fagan *et al.* (1990), tooth transplantation eventually ceased to be a popular procedure in the 19th century, when failures became public and transmission of diseases such as syphilis was feared.

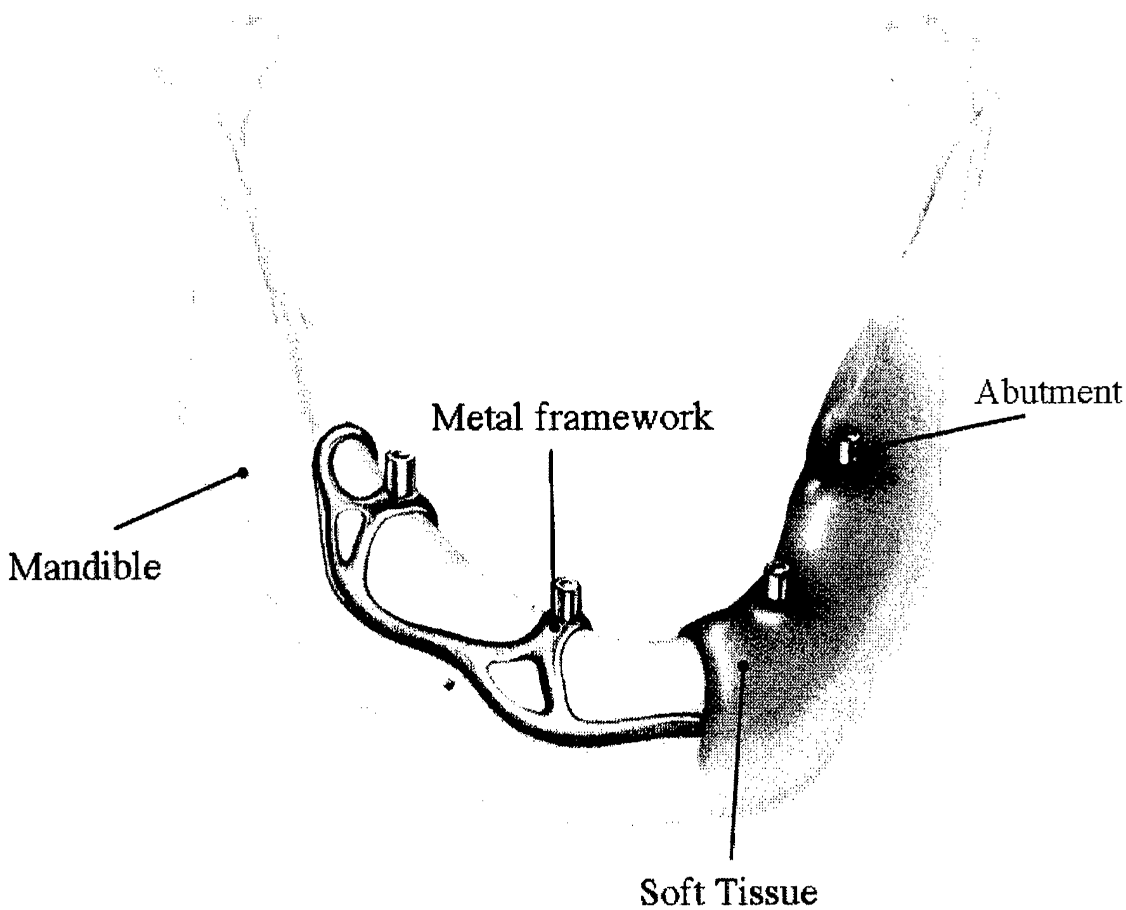
In more modern times, a host of biomaterials have been employed to replace the roots of natural teeth, with varying degree of success. Metals such as platinum, lead, silver, steel, cobalt alloys, and titanium have been used. In addition the use of porcelain, carbon, sapphire, alumina, calcium phosphates, and dental acrylic resin have also been attempted. Dental materials and techniques have now improved to the point where modern dentistry can replace missing teeth with a prosthesis that can be functionally and aesthetically similar to the natural dentition (Fagan *et al.*, 1990).

B. Dental Implant Types

The development and evolution of implant dentistry play an important role in the modern options for the replacement of missing teeth. According to Anusavice (1996), there are basically three main types of implants. These include the subperiosteal implant, a framework that rest over the bone, but does not penetrate it; the transosteal implant, which penetrates completely through the anterior mandible, and the endosseous implant, which is placed into the bone.

Subperiosteal implants (figure 1), are placed over the bony ridge and with transmucosal connections that serve as attachments for a removable overdenture. These implant are generally used when insufficient bone is available for the use of endosseous implants. Linkow (1970) recommends their use only in mandibles with a greatly resorbed ridge. These implants are always custom made and usually require two surgeries. In the first stage surgery the bone is exposed and an impression is made. From the resulting cast, a framework is fabricated and inserted at second surgical procedure. The mucoperiosteal tissue heals over the implant, which is precisely fitted to the contours of the cortical bone, and hold the implant in place. A new technique using CAD-CAM technology has been developed, which allows the

Figure 1: The subperiosteal implant, consist of a metal framework that attaches on top of the bone but underneath the soft tissue.


Metal framework
Abutment
Mandible
Soft Tissue

fabrication of the framework from computerized tomography, thereby requiring only one surgical procedure (Cranin, 1993).

The transosteal implant (figure 2) was designed for the anterior region of the mandible. This implant is composed of individual pins (usually five, seven or nine) which are attached to a plate. The pins are inserted into holes drilled through the inferior border of the mandible to the alveolar crest from an external surgical approach by a submental skin incision. Complications with this implant system include poor oral health and saucerization of bone around the pins, which appears to increase over time (Linkow 1993). Although the subperiosteal and transosteal implants may be advocated by some practitioners, nearly all implants placed today are of the endosseous variety (Cranin, 1993).

C. Endosseous Implants

The endosseous implants are those placed within the bone and which, after healing, serve as anchorage for the dental prosthesis. These implants appear to offer the best solution in terms of clinical limitations and overall success. Reports of Adell *et al.* (1981), suggested a high success rate over a 15 year period for root form implants, when careful attention is paid to the surgical techniques and post operative follow-up. The majority of implants placed today are of the endosseous variety (Cranin, 1993). The encouraging results of the endosseous implants, have paved the way for the introduction of a variety of designs. These implant have been shaped as blades, spirals, screws, cylinders and cones. Blades were very popular in the past, but

Figure 2: The transosteal implant are limited to the mandible and are inserted form an extraoral approach through the inferior border of the mandible.

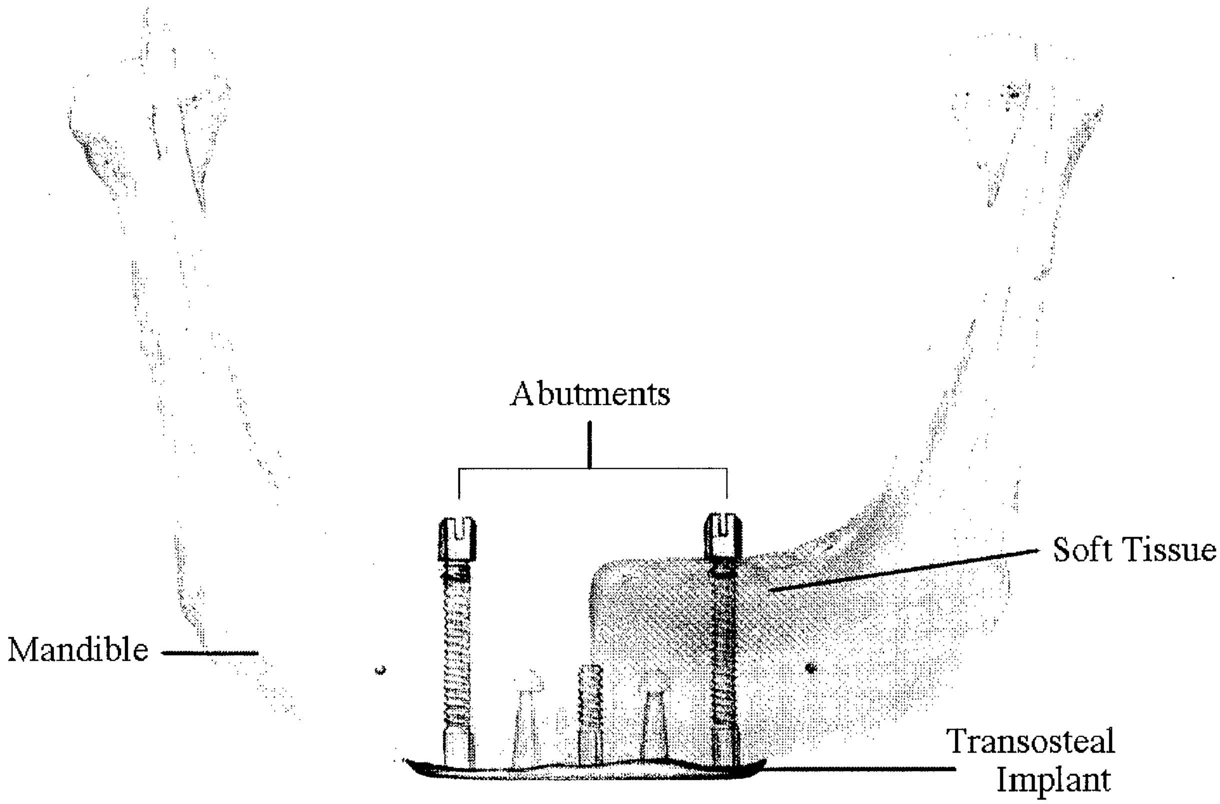

Abutments
Soft Tissue
Mandible
Transosteal
Implant

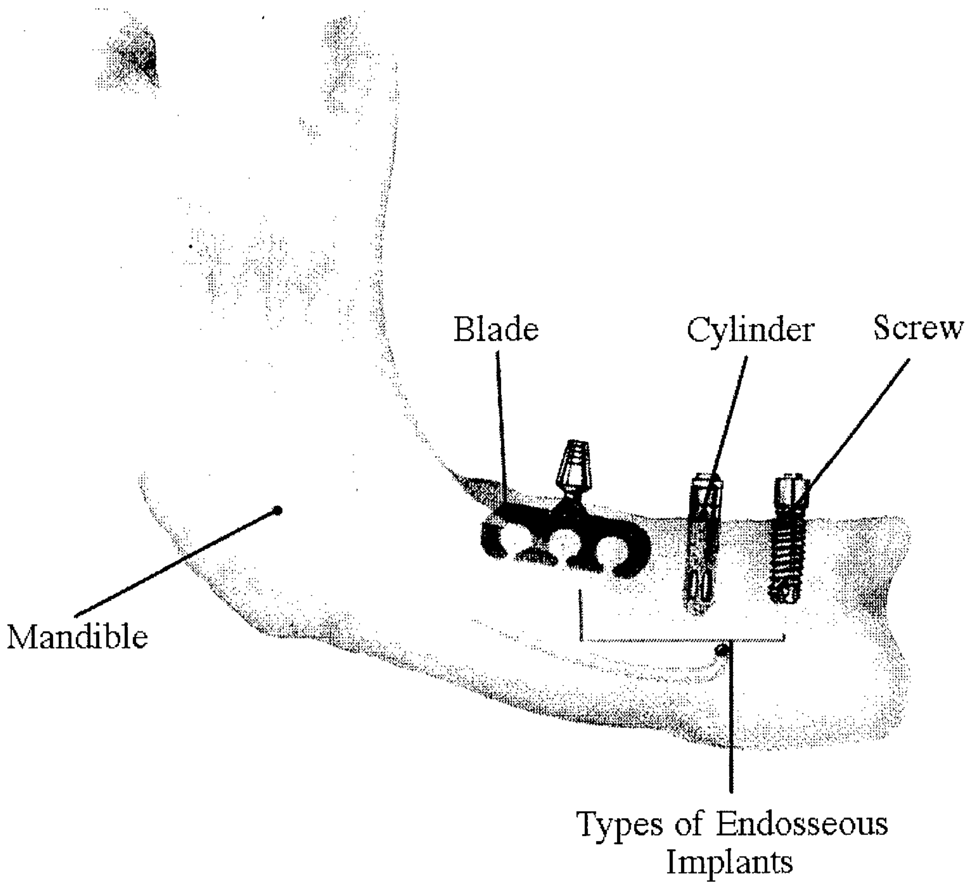
Figure 3: The endosseous implants are placed within the bone.

Three main types:

a. blade

b. cylinder

c. screw

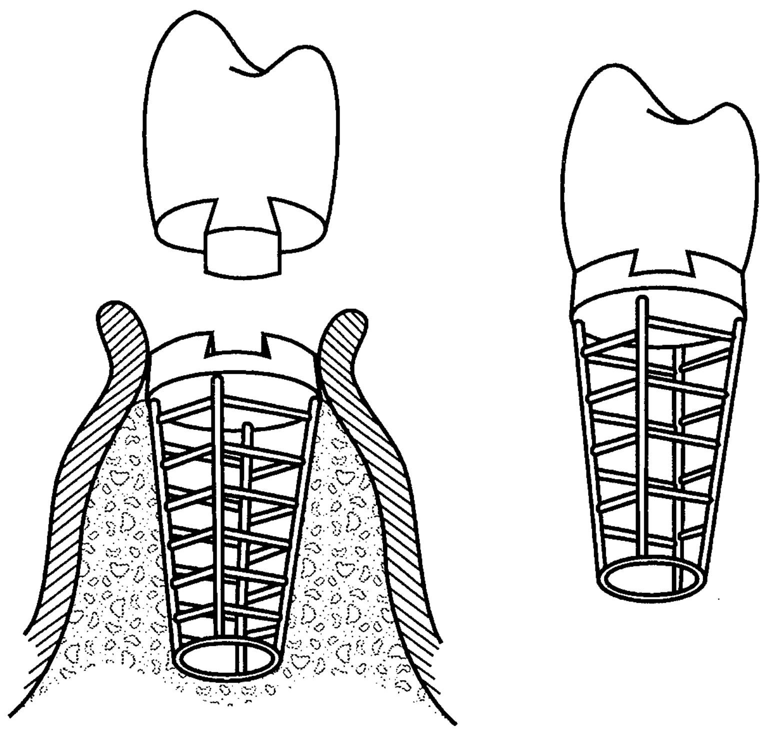

Blade
Cylinder
Screw
Mandible
Types of Endosseous
Implants

cylinders and screws are most commonly used presently (Figure 3). The cylindrical variety can be also subdivided into threaded or non-threaded, with dense or porous surfaces (Cranin, 1993).

One of the earliest endosseous implants was the Greenfield Implant (Figure 4) designed by Edwin J. Greenfield of Kansas (Greenfield, 1909). This implant consisted of a system composed of an irridioplatinum alloy latticed root shaped cage, and a friction fit crown. Alvin E. and Moses Strock (1939) experimented with the more biomechanically favorable screw design. They utilized Vitalium, which is a cobalt-chromium-molybdenum alloy. They limited themselves to single tooth restorations to eliminate occlusal factors and other confounding variables present with long span restorations. The Strock's were also the first to try an unloaded healing phase. Their success was variable, but their biggest contribution to implant dentistry was in their approach to implant experimentation with a strictly controlled scientific method.

Others followed with a wide variety of implants shapes and materials. Two of these systems were vitreous carbon implants and the Linkow spiral post vent-plant and blade plant implant systems. Vitreous carbon implants were cores of stainless steel covered by 99.99% pure carbon. They were used as single free standing units or splinted to adjacent teeth. After insertion, they were allowed to heal for a minimum of five months before fabricating the final prosthesis.. According to Albrektsson *et al.* (1986), the major complication of these implants were substantial bone loss, and in some cases osteomyelitis and paresthesia. Leonard I. Linkow introduced the spiral post vent-plant made of tantalum, in 1963. Linkow (1970) experimented by altering the

Figure 4: This is an illustration of a Greenfield Implant (1909),one of the earliest dental implant designed by Edwin J. Greenfield.



shape of the implant and by coating the implant with aluminum oxide. In 1967, Linkow modified his vent-plant implant system further into a blade. This blade implant was tapped into place in a slit that was made in the cortical plate bone. Linkow's implants were anchored by fibrous encapsulation, which was originally believed to mimic the periodontal membrane (Fagan 1990). However, vent-plants and blade implants failures were accompanied with significant morbidity.

D. Osseointegration

According to Cranin and Dennison (1973), endosseous implants develop a border zone of connective tissue encapsulating the implant. This tissue was called "pseudoperiodontium" and was considered desirable for the success of the implant. Brånemark *et al.* (1977), stated that this "pseudoperiodontium" cannot effect the necessary permanent relation between the implant surface and the bone, and suffers repeated mechanical and chemical injuries from the oral cavity. Over a period of time this situation promotes plaque accumulation, gingival inflammation and migration of the oral epithelium leading to rejection of the implant. Furthermore, the soft connective tissue that supports the implant is mobile, which promotes the passage of microbial contamination from the oral cavity to the implant. Brånemark concluded that the long term prognosis for connective tissue anchored implants was questionable on the basis of both biological considerations and clinical experience. For clinical and biological success to be achieved, permanent tissue or true bone anchorage ("osseointegration") must be achieved.

Brånemark (1983), defined osseointegration as a direct contact between living bone and the implant without the interposition of fibrous tissue. Albrektsson *et al.* (1981), described osseointegration as a direct bone to implant contact on the light microscopic level. Albrektsson studied the interface zone between bone and implant using x-rays, scanning electron microscopy, and histology. His study showed a very close relation between the titanium implant and bone. The pattern of anchorage of the collagen fibers to titanium were described as very similar to that of Sharpey's fibers to bone. Soft tissues were closely adhered to the titanium implant, forming a biological seal, and therefore preventing microorganism infiltration along the implant.

E. The Brånemark Dental Implant

Brånemark (1983), discovered osseointegration incidentally, in 1952 while performing vital microscopic studies of the bone marrow of rabbit fibulas. Using a special microscope with a screw design optical chamber, Brånemark studied in vivo and in situ the effects of various injuries to bone by observing marrow healing and damage to the capillaries. The optical chamber, made of commercially pure titanium, was implanted into the bone marrow of rabbit fibulas, and allowed to heal in place. Brånemark found that the optical chamber could not be removed after healing had taken place. Further investigation led to the observation that bone had grown inseparably into very thin spaces of the titanium chamber. These experiments led to other investigations on the repair of major mandibular and tibial defects in rabbits and dogs.

Separate studies (Albreksson *et al.*, 1981, Kasemo, 1983) were done on the healing of various tooth-root form titanium implants. These root form implants were named fixtures, a name that is still used today for that portion of the implant system that osseointegrates with bone. These studies showed that the success of the implant depends on a gentle surgical technique with an undisturbed healing phase using a material that is biocompatible to the host.

F. Surgical Technique

At the first stage surgery, holes are cautiously bored in the bone using copious irrigation to prevent traumatic heat from damaging the bone around the implant site. The hole is enlarged with a delicate surgical technique by using progressively a series of drills at a very low controlled speed. Erickson and Albrektsson (1983), found that temperature elevation above 47° C significantly disturbed the subsequent osseointegration. Following the placement of the fixtures in the bone, the mucosa is sutured, covering the implants for the healing period. The importance of a delicate surgical technique was stressed by Brånemark (1983) when he wrote, "In order to create osseointegration, the preparation of the bone must be done so that minimal tissue injury is produced". Healing time is based upon the healing potential for the bone. In the maxilla, it is typical to allow the implant fixtures to osseointegrate for a minimum of six months. In the mandible, a minimum of three months healing appears to be sufficient.

During the second stage surgery, the mucoperiosteum over the fixture is reflected and a transepithelial healing abutment or cylinder is attached to the implant fixture. If used, the healing abutment allows for final soft tissue contours to develop prior to placing the definitive abutment cylinder. The abutment cylinder, in turn, provides an attachment for a prosthetic superstructure. The superstructure is either the final prosthesis itself or is used to attach and support the final prosthesis. In some cases when an impression of the implant position is made at the first stage surgery, a custom made provisional restoration can be prepared and placed at stage two, instead of placing a conventional transepithelial healing abutment. Idealized anatomic and functional contours are developed in the custom made provisional, resulting in optimum function and esthetics in the final restoration.

G. Biocompatibility

Anusavice (1996), measures biocompatibility on the basis of localized cytotoxicity, systemic response, allergenicity, and carcinogenicity. Based on these criteria, a biocompatible material used in dentistry should: not be harmful to the pulp or soft tissues; not contain toxic diffusable substances that can be released and absorbed by the tissues causing a localized or systemic toxic response; be free of potentially sensitizing agents that are likely to cause an allergic response, and not have a carcinogenic potential. According to Williams (1987), biocompatibility has been defined as the ability of a material to perform with an appropriate host response in a specific application. The implant material is affected by the surrounding chemistry of the healing tissues (Gross, 1988). Depending on the material, ions may leach out, corrosion may take place, and other electrochemical processes may occur. These events may create changes in the physical properties and chemical composition of the implant material. Metals that ionize easily in body tissues are more prone to rejection, while metals that are relatively inert to the body are more easily accepted and well tolerated. According to some authors, (Albrektsson 1981, Kasemo 1983, Anusavice 1996) osseointegration is only possible with ceramic implants or with passivated metal implants. Titanium is always coated with an oxide layer, so the metal is never in direct contact with the surrounding tissues. According to Kasemo (1983), this oxide layer is approximately 50 to 100 angstroms thick and is composed of a combination of TiO, TiO_2, Ti_2O_3 and Ti_3O_4. According to Albrektsson *et al.* (1981) and Kasemo (1983), the surface coating on titanium can be regarded as a ceramic. They stated: "It is, therefore, titanium's oxide coating that makes it so well accepted by host tissues".

According to Anusavice (1996), at least two types of ceramic materials have been developed for dental implants. One is bioactive and the other is nonreactive. The bioactive materials are ceramics or glasses that are rich in calcium and phosphate such as hydroxyapatite and Bioglass. Hydroxyapatite is a mineral with the formula $Ca_{10}(PO_4)_6(OH)_2$, it is very similar to the constituents of bones and teeth. However the inadequate strength and ductility of this ceramic, when bending or tensile forces are applied, has limited its use to areas of very low stress areas application. The other bioactive material is Bioglass, which is a dense ceramic material made from CaO, NaO_2, P_2O_5, and SiO_2. Bioglass reacts with tissue fluid to form a calcium phosphorus layer. Once a sufficient concentration of phosphorus is present at the surface, osteoblasts begin to proliferate. Collagen fibrils are produced and become incorporated into the calcium phosphorus gel, the fibrils are then anchored to the calcium phosphorus crystals. This bonding layer has been shown to be 100 to 200 microns (μm) thick, roughly 100 times the thickness of comparable layers formed by hydroxyapatite. The other type of ceramic material are the nonreactive family of ceramics, which include alumina and sapphire. They do not have the necessary composition to actively participate in the process of bone deposition. Aluminum oxide (Al_2O_3) either polycrystalline or single crystalline (sapphire) has shown evidence of success in clinical studies.

H. Criteria for Implant Success

According to Schnitman and Shulman (1979), rapid development and increased use of dental implants caused leaders in the dental implant field to realize that practitioners needed guidance in the use of dental implants. The Harvard Conference of 1978 was one of the first attempts to developed a consensus on guidelines for implant use. Definitions of success, benefit, and risks of different implant types were described. According to Albreksson *et al.* (1986) this conference was designed as a retrospective study to review clinical data on subperiosteal, transosseal (staple), vitreous carbon, and blade implants. Significant studies on osseointegration were ignored.

A conference on Osseointegration in Clinical Dentistry was held in Toronto, Canada in 1982. This conference reviewed the science, biomaterials, techniques, and clinical research findings of the Brånemark osseointegrated implant system. The conference not only created great academic interest in the science of dental implants, but led to updated definitions of success and benefits and risks (Zarb, 1983). Albreksson *et al.* (1986) proposed that part of the implant success criteria should include clinical immobility of the fixture and no radiographic evidence of peri-implant radiolucency.

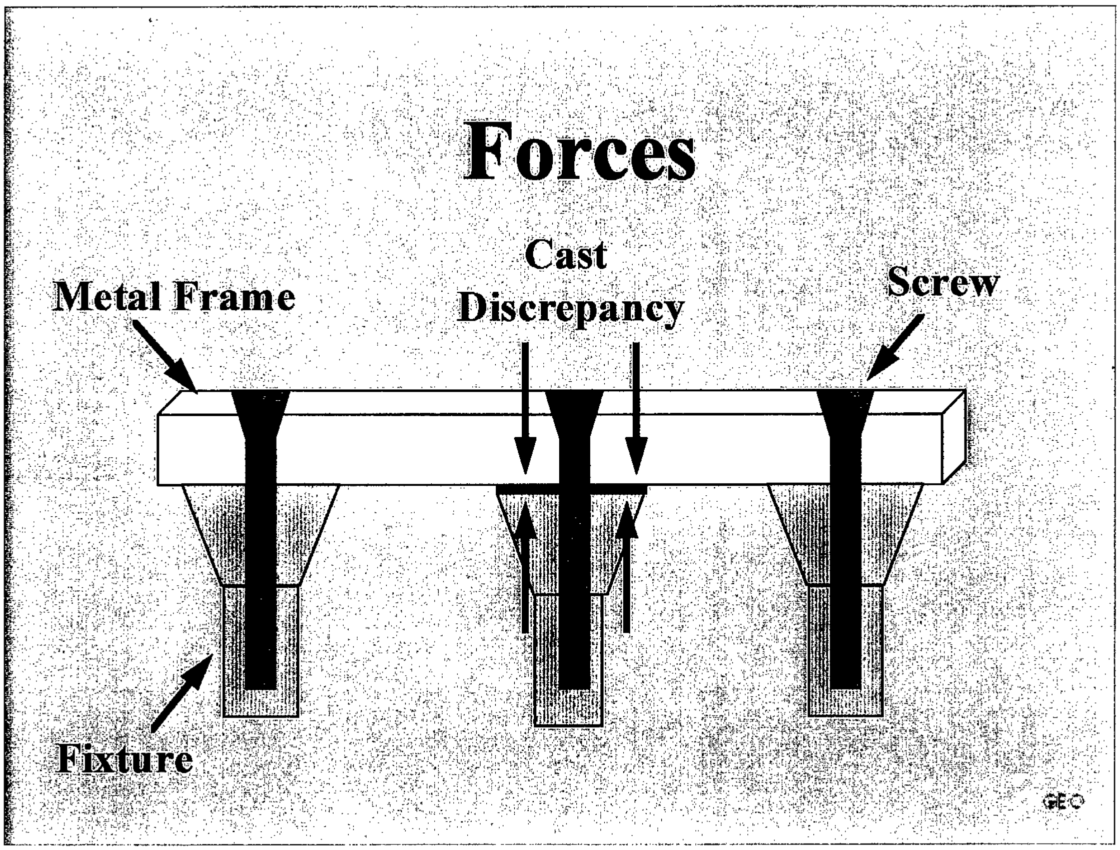
Albrektsson *et al.* (1983) described various ways to clinically evaluate bone integration once the implant is placed. The osseointegrated implant should be completely stable in the bone. It should not be rotated or exhibit any looseness or movement. Radiographic examination should reveal normal trabecular bone around the implant. Albreksson also stated that the success of any dental implant procedure is dependent on the interrelation of multiple factors. Biocompatibility of the implant material and the health and quality of the recipient bone are factors to consider in the initial phase. An atraumatic surgical technique and an undisturbed healing phase are essential to avoid bone damage and allow the implant to osseointegrate. Implant shape and surface characteristics are important to create a better loading force distribution and bone-implant interlocking. A prosthetic design that provides a passive fit, an incremental loading phase, cosmetics, and hygienic considerations are critical.

I. Prosthodontic complications:

Despite the fact that modern methods for implant therapies can be quite successful, expectations of the patient and the dentist are sometimes not fulfilled. The concept of osseointegration has revolutionized prosthodontics options for the replacement of missing teeth and related oral structures. Brånemark (1983), stated that the principle of osseointegration in clinical dentistry depends on an understanding of the reparative and healing capacities of the hard and soft tissues and that this concept has revolutionized prosthodontics options for the replacement of missing teeth and related oral structures. A 15 year study of osseointegrated implants by Adell *et al.* (1981), stated that "Osseointegration implies a firm, direct and lasting connection between vital bone and screw-shaped titanium implants of defined finish and geometry. Osseointegration can only be achieved and maintained by a gentle surgical technique, a long healing time and a proper stress distribution when in function." Adell also stated that an absolute passive fit must be obtained between the prosthesis and the abutment to prevent mechanical complications. If an absolutely passive fit between the prosthesis and the abutment cannot be obtained, stress is transmitted to the fixtures and the prosthesis locking screws.

Balshi (1989), described dental implant complications in six major categories: esthetics, phonetics, function, biology, mechanics and ergonomics. According to Balshi, when fractures occur in the retaining screw in implant prostheses, there is a strong possibility of discrepancies or inaccuracy of fit between the framework and the implant. Rangert *et al.* (1989), noted that failures due to mechanical overloading can be

Figure 5: Diagrammatic representation of undesirable forces to the screw and other implant components when a non-passive fit is not obtained.


Forces
Cast
Discrepancy
Metal Frame
Screw
Fixture
GEO

minimized by carefully evaluating implant position, prosthesis design, and passive fit of the framework to the implant anchoring unit. These factors could minimize forces to the implant and surrounding bone. When a passive fit is not obtained, space is evident between the gold cylinder and the implant abutment. This opening in the screw joint and resultant loosening of the screw, are the primary causes of gold screw fracture, due to constant tension forces (figure 5). Rangert also stated that the tension on the gold screw is the critical force to be considered. Compression forces will not overload the gold screws. Tension can be induced by a direct tension force, or from a bending moment. Millington *et al.* (1995) stated that an accurate fit is important in reducing stresses in the superstructure implant components and the bone adjacent to the implants. He also stated that misfit may cause pain and discomfort, contribute to loosening or fracture of implant screws, implant components or loss of osseointegration. The level of stresses caused by fit discrepancies are dependent on the interabutment distance, size and location of the gap, and the shape, dimensions, and stiffness of the metal superstructure. Meijer *et al.* (1992), and Millington *et al.* (1995), also mentioned that the length, number, and distribution of implants, the shape and dimensions of the arch, and the stiffness of the bone play a part in the final stress distribution.

According to Patterson and Johns (1992), metal fatigue is perhaps the most common cause of structural failure in implant retained prostheses. If the quality of fit between the implant and the restoration is not passive, the screw will experience the full loading and its fatigue life will be reduced. Fatigue of the retaining screw occurs under repeated loading at stress levels below the ultimate strength of the material. Cracks grows from the location of maximum stress and, if not detected, can lead to sudden and catastrophic failure. In the Brånemark system, this screw connection has been designed as a fail-safe mechanism. Non-passive fit prevent constant forces from being transmitted to the implant, implant components and its surrounding bone, screw fracture may occurs when excess force is applied. Cronin (1992), stated that to prevent traumatic loading of the implant fixture, a precise fit is necessary between the implant abutment and the superstructure. He described the fit with the term of "precise passive prosthesis".

Screw fracture is not the only complication when a passive fit is not achieved. As shown by Worthington *et al.* (1987), Balshi (1989), Brånemark (1988), and Tan *et al.* (1993), fracture of the prosthesis implant component, as well as loss of osseointegration could be attributed to non passive fit. For implant longevity, passive fit is imperative.

It is difficult to fabricate an implant prosthesis with a high degree of accuracy of fit, due to the dimensional changes that occur in the different materials used in the fabrication process. Multiple references have been made regarding the difficulty of achieving passive fit of cast superstructures to two or more implants. Potential distortion of implant prostheses may be complex, and may be magnified by both the relatively large mass of alloy cast and the size and shape of the prosthesis framework. Tan *et al.* (1993), described a three-dimensional analysis of the casting accuracy of the one piece, osseointegrated implant retained prostheses. He found significant differences in translational and rotational displacements between cylinders of the same casting. He also stated that even small rotational displacements may manifest large gap discrepancies because of the "moment arm" effect.

According to Misch (1993) the following factors interrelate and affect the fabrication of a completely passive superstructure; elastic deformation and dimensional shrinkage of elastic impression materials, implant analog variance; die stone and investment expansion, clinical methods of casting verification, wax shrinkage, metal shrinkage, soldering, variable torque of the screws, and the number, position and distance of the implants. Craig (1993), mentioned that linear casting shrinkage of gold alloys ranges from 1.25% to 1.7%, while that of base metals is about 2.3%.

Various techniques have been suggested to correct, improve or compensate for these inaccuracies. Assif *et al.* (1992) and Assif *et al.* (1994) studied different implant transfer impression techniques to assess the accuracy of stone master cast fabrication. The use of acrylic resin to splint square transfer copings gave the best results, while unsplinted smooth transfer copings were unacceptable. Assif also stated that dentists can detect differences in the fit of the framework in the range of 30 microns, while patient perception to pressure is in the range of 15 microns. Frameworks must be re-evaluated for accuracy if pain or pressure is perceived by the patient. Ivanhoe *et al.* (1991), recommended a technique utilizing acrylic resin added in increments to conventional direct transfer impression copings, using minimal gap connections. This technique provided less shrinkage potential and distortion of the entire acrylic mass. McCartney and Pearson (1994) stated that regardless of the impression procedure, it is highly recommended to verify the accuracy of the master cast before starting fabrication of the framework. If there is any inaccuracy observed, a corrected cast procedure or new impression should be accomplished. Knudson *et al.* (1989), noted that verification of master cast accuracy enhances the probability of passive fit of the prosthesis.

Casting shrinkage of long span metal frameworks, combined with the rigid implant to bone relationship makes it unlikely that a one piece framework will fit passively to all the supporting implants or abutments. Balshi and Fox (1986) stated that the ability of the periodontium to adapt or compensate is advantageous to the fabrication of fixed prostheses. Microscopic movements within the periodontium help to compensate for inaccuracies that usually occur during a fixed prosthesis fabrication. Because the osseointegrated implant lacks this type of periodontal interface and is solidly attached to bone, casting inaccuracies are uncompensated and do not provide a passive fit. Because of these factors, other methods for improving framework fit have been developed.

According to Hobo *et al.* (1989), the most common method used to fabricate the implant super-structure is to cast dental alloys to a machined gold cylinder. If the casting does not fit, cutting and soldering the framework is one alternative to correct the inaccuracies. However, soldering is time consuming and final results may not be consistent or clinically acceptable. Willis and Nicholls (1980), stated that an insufficient gap between the segments to be soldered will cause dimensional change when the heated assembly expands. An excessively large gap may provide either a weaker joint in conjunction with casting distortion and deformation due to shrinkage of the solder during solidification. Consequently, because of the variable dimensional changes that can occur, Misch (1993) recommended that large castings should be fabricated in sections, verified intraorally, and connected rigidly while in place intraorally.

Seller (1989) introduced a framework design that consisted of components that were joined by cement intraorally, allowing a framework-abutment adaptation within the 5 μm range. In this technique, the abutment sleeves and the retaining screw sleeves are cemented to the cast member. This framework design combines the passive adaptation of a cemented prosthesis with the retrievability of a screw retained prosthesis.

Stumpell and Quon (1993) stated that achieving a passive framework fit is difficult, if not impossible, and recommended a technique in which pre-machined titanium abutment cylinders are luted with composite resin to a cast framework. Stumpell mentioned that debonding is a potential problem with this technique. But he stated that these problems can be solved with the repetition of the luting process. McCartney and Doud (1993) recommended soldering pre-machined gold cylinders to a cast superstructure. In this technique, the framework is cast with only one gold cylinder. Spacers are placed in the other gold cylinder positions. After the framework is cast and adjusted, the other gold cylinders are soldered in place. Sutherman and Hallam (1990) recommended a technique of sectioning and soldering the frameworks. A modified casting technique has also described by Parel (1989).

Sjogren *et al.* (1988) recommended a method of laser welding titanium frameworks. Jemt and Linden (1992) recommended welding together pre-machined titanium framework sections, using the Sjogren laser welding technique. Two techniques were described by Jemt and Lindem; the first consisted of welding framework sections after adjustment and proper orientation; the second consisted of welding titanium sections to an unalloyed titanium bar. Hulling and Clark (1977) noted that laser welding gave less post-jointing distortion and better reliability than soldering. According to Weber and Frank (1993), welding implies that no other alloy is needed to join the parts together. Laser welding is a surface phenomenon and may have different penetration depths, what may induce dimensional changes in the welded joint. According to Sjogren *et al.* (1988) it could not be excluded that the chemical composition of the highly reactive titanium metal may be altered in the welded joint and this might in turn influence mechanical properties in the region.

It is difficult to fabricate a completely accurate framework or superstructure. The techniques previously mentioned can improve the fit, but may bring other problems. Soldering is time consuming and the results are not always consistant or accurate. Methods using cement or composite resin solve the problem of fit, but may reduce longevity due to the limited life of these materials in the oral cavity. One of the most promising techniques reviewed was laser welding of framework segments, but this technique requires more investigation.

Linehan and Windeler (1994) presented a new technique in which an electric discharge machining (EDM) process was used to correct casting inaccuracies and obtain a passive fit between the implant superstructure and the implant abutment.

J. Electric Discharge Machining:

Electric discharge machining (EDM) is a metal removal process that uses a series of electrical sparks to erode material from a work piece under carefully control conditions. EDM is known by the name of spark erosion in Europe, and also by the less accurate terms of "electro erosion", "electrolitic machining" and "spark machining". EDM is considered a non-traditional machining process (Weller, 1984). This process is different from conventional machining processes in the manner in which the tool contacts the workpiece. In the EDM process there is no mechanical force between the tool and the workpiece. Instead electrical discharges or sparks machine the workpiece. The cutting tool in the EDM process is called the electrode. The electrode does not physically contact the part being machined, but merely provides a platform from which the sparking originates. The electrode remains the length of the spark away of the workpiece. Thermal energy of the spark is used to machine the workpiece. The area where the sparking takes place is surrounded by a dielectric medium (Noaker, 1991). The shape of the electrode determines the shape of the part being machined. An EDM electrode must be an exact reverse or mirror image of the finished form or shape desired in the workpiece. Since the sparking is caused by the flow of electricity, the electrode and the workpiece must be of materials that conduct electrical current. During the machining process the workpiece is normally secured to the table and an electrode is attached to the vertical ram above the workpiece. The electrode is then brought in close proximity to the workpiece. A servo control of the ram workhead automatically maintains a gap distance between the electrode and the workpiece, using a reference voltage. When the gap distance is established by the servo mechanism an electrical discharge will take place between the electrode and the workpiece, removing a minute particle of the workpiece at the point where the gap is the smallest.

It is not only the electric current flow that removes material from the workpiece. According to Weimer (1988) "It is turning that current ON and OFF, pulsing it, that produces the thermal action of charged particles to melt and eject metal." The amount of time allowed for each pulse is measured in microseconds (μsec) and referred to in the EDM process as "on-time". Between pulses there is a pause, when no energy passes through the electrode. This also is measured in (μsec) and referred to as the "off-time". The process occurs with the electrode and workpiece submerged in an insulating oil called dielectric fluid.

K. Electrical terminology and basic concepts

The earliest recorded observations about electricity date from about 600 BC and are attributed to the Greek philosopher Thales of Miletus. He noted that amber, a fossil resin, takes a charge of static electricity when it is rubbed. He called this static force "elektron". The word electricity is derived from this Greek term.

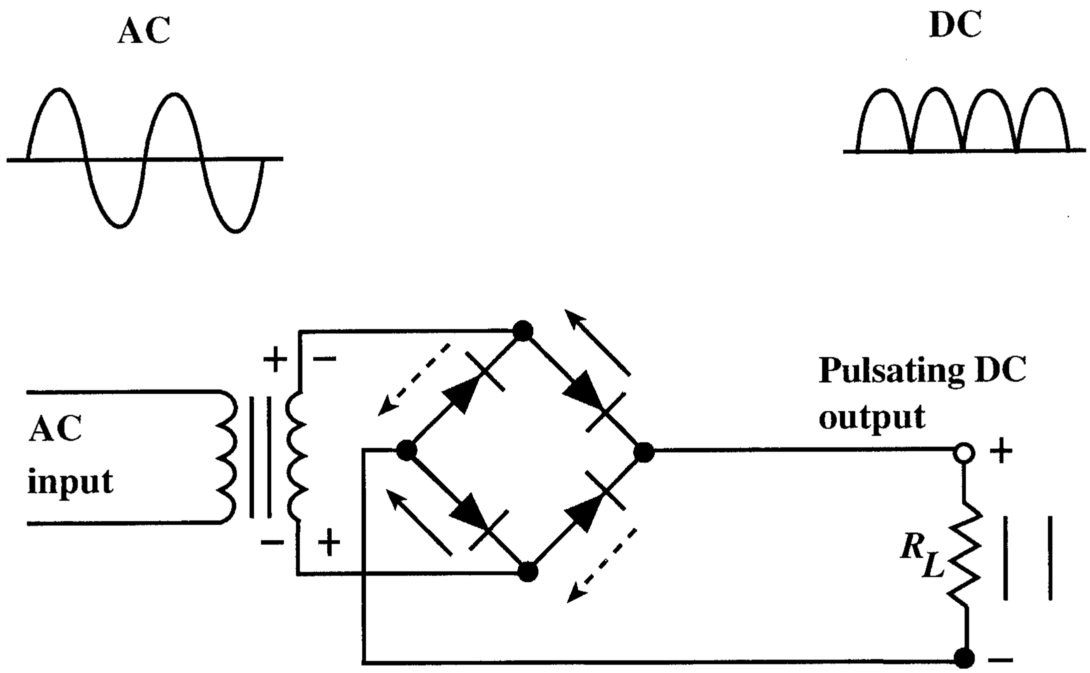
Electrons are the smallest and lightest of particles. They are said to have a negative charge, meaning that they are surrounded by a field of force that will react in an electrically negative manner on anything that is electrically charged and brought within the limits of the field. Protons are about 1800 times as massive as electrons and have a positive electric field surrounding them. The electric field near the electron is quite strong. To produce movement of an electron, it is necessary to have either a negatively charged field to push it, a positively charge to pull it, or as normally occurs in an electric circuit, both a negative and a positive charge. According to Shrader (1993) the three controlling factors always present in electric circuits are the electromotive force (EMF), the current and the resistance. The EMF is the electron moving force in a circuit that pushes and pulls electrons through the circuit. The unit of measurement of electric pressure or EMF is the volt (V). A volt can be defined as the pressure require to force a current through a resistance. Current is the progressive movement of free electrons along a conductor, forced into motion by an electromotive force. The amount of current in a circuit is measured in amperes, (A) or "amp". An ampere is a unit of measure that describes the number of electrons passing a single point in an electric circuit in one second. Therefore, an ampere describes a rate of electron flow. Resistance is any opposing effect that hinders free electron progress through a conductor in a circuit when an EMF or voltage attempts to produce a current in the circuit. If the material of the circuit is made of atoms or molecules with no free electrons, the EMF can not produce a current in such an insulator, dielectric or nonconductor.

In most metals, atoms are constantly losing and regaining free electrons. Metal may be thought of as constantly undergoing ionization and are therefore good electric conductors. Atoms in a gas are not ionized, making gas an insulator or dielectric. If the EMF is developed across an area in which gas is present, some of the outer orbiting electrons are attracted to the positive terminal of the EMF and the remainder of the atoms will be attracted toward the negative terminal with increasing pressure , one or more free electrons may be torn from the atoms. The atoms are then ionized and a current flows through the gas. For any gas at a given pressure and temperature there a certain voltage value that will produce ionization. Below this voltage, the number of ionized atoms is negligible. Above the critical value, many atoms are ionized, producing heavy current flow, which tends to maintain the voltage across the gas as an electric conductor. Examples of ionization of gases can be found naturally occurring as lightning as well as fluorescent lights. Ionization plays an important part in the EDM process.

Electrical currents may be described as alternating current (AC) and direct current (DC). In alternating current the electron flow reverses or alternates cyclically and usually changes amplitude in a more or less regular manner. In direct current there is no variation of the amplitude of the current and voltage. The flow of electrons in direct current is unidirectional while in alternating current is bi-directional. The EDM power supply has a rectifier that changes the alternating current to a pulsating direct current, in which the energy flows in one direction but the amplitude drops to zero periodically (Figure 6).

Figure 6: Alternating Current (AC) and Direct Current (DC) electrical waves.

Diagram of an AC - DC electrical rectifier.



AC
DC
Pulsating DC output
AC input
+
−
R_L

L. The Thermoelectric Theory

While there are several theories of how the EDM process actually works, most of the evidence supports a thermoelectric model. Thermoelectricity is best described as heat and electricity working together. Even though the dielectric fluid is an insulator, an EMF can cause the fluid to break down and ionize (Poco, 1993). When the fluid is ionized, the electrical current is allowed to pass from the electrode to the workpiece.

Poco (1993) described the thermoelectric concept that occurs in each EDM cycle as follow: An electrically charged electrode is brought near the workpiece, between them is an insulating oil, known as dielectric fluid (Figure 7-a). As the voltage increases where the distance between the electrode and the workpiece is least, the dielectric fluid begin to loose its insulating properties and ionic particles initiate fluid breakdown. A narrow channel is developed in the strongest part of the field (Figure 7-b) At this point voltage reaches its peak, but current is still zero. Fluid become less of an insulator, current flow is established and heat builds up rapidly. This vaporizes some of the fluid, creating a discharge channel between the electrode and the workpiece (Figure 7-c). As the current continues to rise, voltage drops and a vapor bubble is formed around the discharge channel(Figure 7-d). Near the end of the on-time, heat and pressure within the bubble reach their maximum, and the discharge channel becomes a superheated plasma made of vaporized metal and dielectric fluid with an strong current passing through it (Figure 7-e). At the initiation of the off-time, the current and voltage drops to zero, the temperature decreases, and the vapor bubble collapses causing the molten metal to be expelled from the work piece Fresh dielectric

Figure 7: EDM Thermoelectric Theory

7.a).An electrically charged electrode is brought near the workpiece

7.b) Voltage increase, a narrow channel develop in the strongest part of the field

7.c) Current flow is established and heat builds up rapidly. A discharge channel develop between the electrode and the workpiece.

7.d) Current continues to rise, voltage drops and a vapor bubble is formed around the discharge channel.

7.e) Heat and pressure within the bubble reach their maximum.

7.f) Vapor bubble collapses causing the molten metal to be expelled from the work piece.

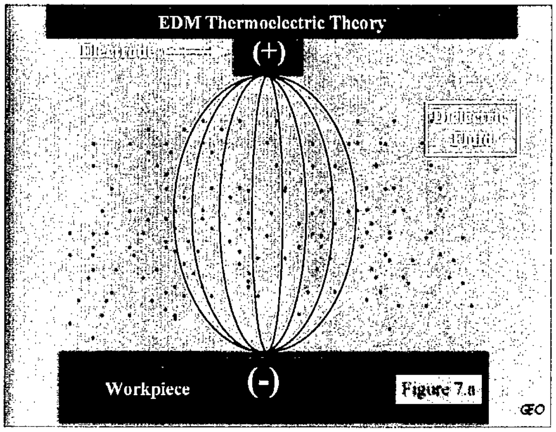


Figure 7.a

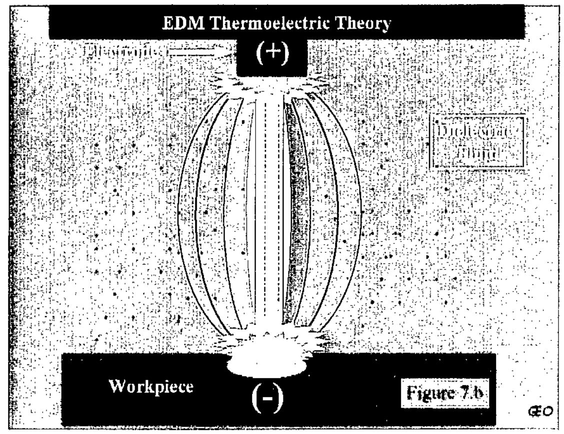


Figure 7.b

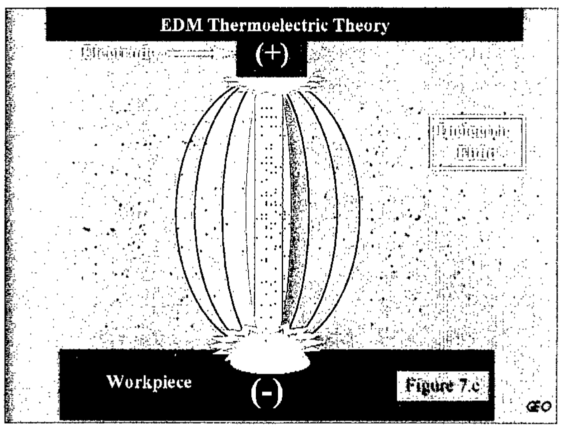


Figure 7.c

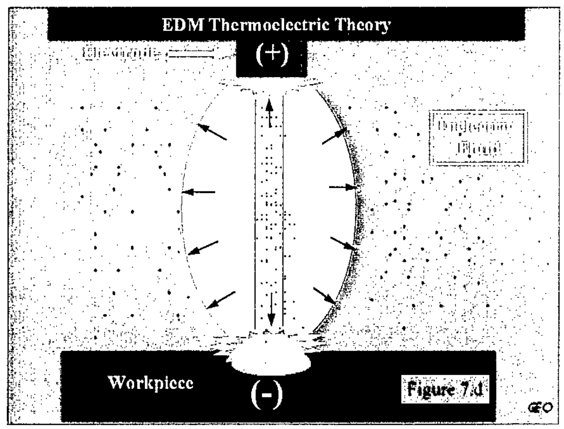


Figure 7.d

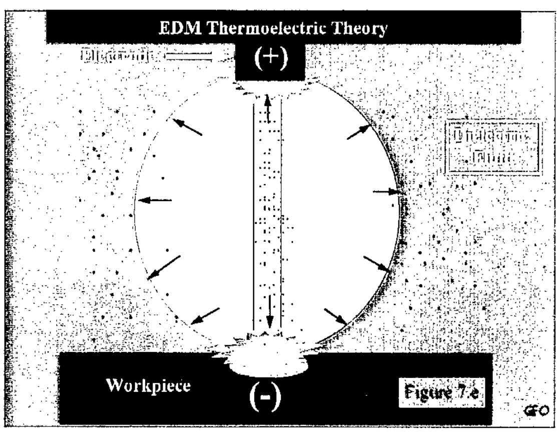


Figure 7.e

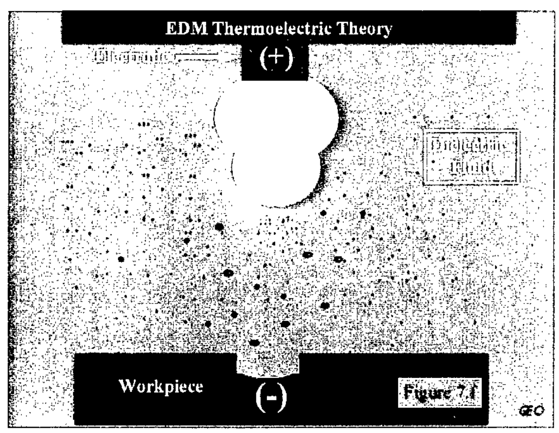


Figure 7.f

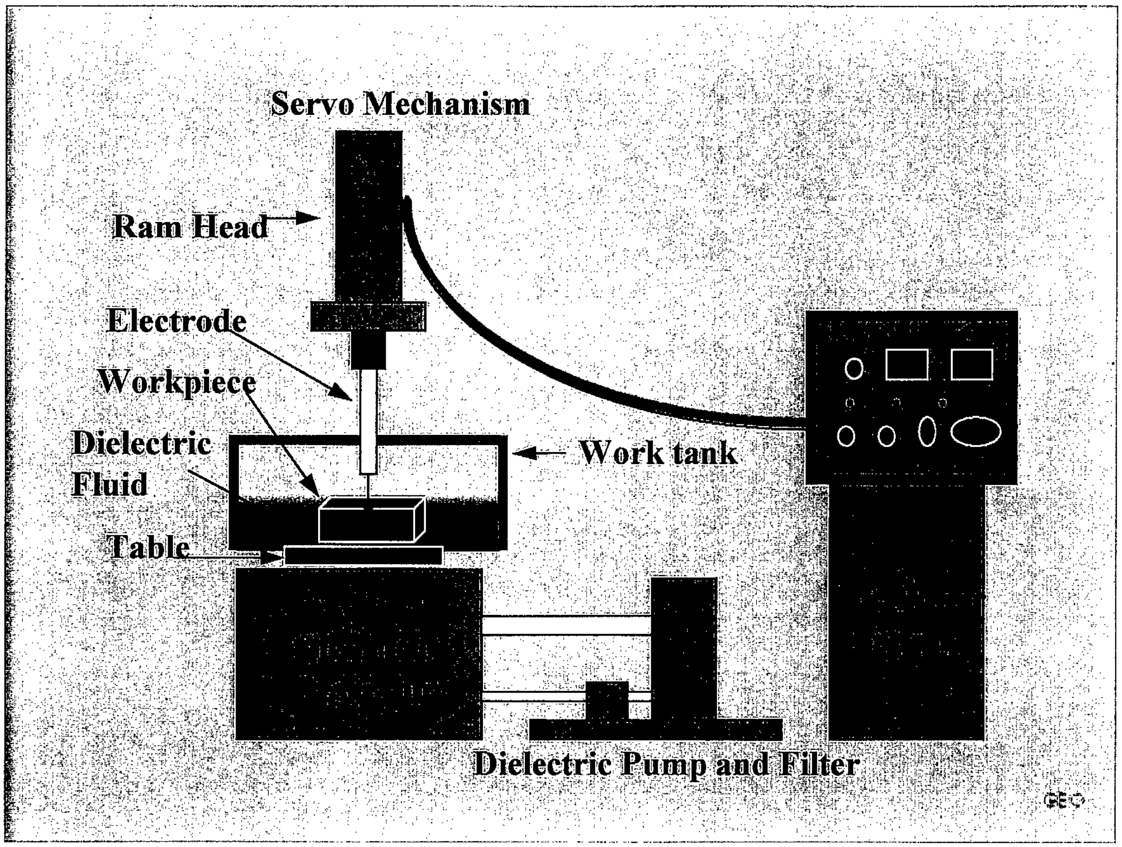
fluid removes the debris and quenches the surface of the workpiece (Figure 7-f). (Jameson,1993) (Poco, 1993).

M. EDM History

The EDM process is not new. According to Weller (1984) the EDM process dates back to the 1940's with two different group of people working on its development. B.R. and N.I. Lazarenko, two brothers who were Russian scientists, studied the erosion rate of electrical contacts. Their study showed that the erosion rate was greater when the contacts were submerged in transformer oil than when exposed to air. Their investigation led to further studies that indicated metals could be shaped by electrical discharges. The Lazarenkos' established a method to electrically machine metals in 1943.

In 1940 , H. L. Stark, H. V. Harding and J. Beaver also investigated the use of electrical sparks to perform machining. They attempted to develop a system to remove broken taps and drills from valuable hydraulic valve bodies, parts needed for aircraft hydraulic system during World War II. According to Kubistant (1993) and Poco (1993), these spark erosion machines were very inefficient and difficult to operate. The electrode was hand fed which resulted in more arcing than sparking, creating damage to the electrode and workpiece. In 1950, the Lazarenko brothers modified and improved the EDM machine. Poco (1993), described the two main contributions of the Lazarenko brothers as the creation of the relaxation circuit (RC) that provided the first dependable control of pulse times, and the addition of a servo control circuit that automatically find

Figure 8: Diagram of the Electric Discharge Machine system components.


Servo Mechanism
Ram Head
Electrode
Workpiece
Dielectric
Fluid
Work tank
Table
Dielectric Pump and Filter

and hold a given gap distance between the electrode and the workpiece. With these two improvements, the EDM process gained acceptance as a production machine tool. Improvement in electronic devices, solid state circuits, and computer numerical controls transformed the EDM process to a machining method capable of performing accurate, dependable, and consistent results.

N. EDM terminology

The basic EDM system has four main components; servo system, power supply or generator, machine tool, and dielectric system. (Figure 8) In the basic ram type EDM system, the ram head is driven up and down with extreme precision by a servo driven system. The servo system is controlled by a microprocessor connected to the power supply. The servo microprocessor senses the gap distance. If the gap distance is too wide, the servo system is instructed to lower the ram head. When the first spark jumps the gap, the downward travel of the ram head stops. The gap distance setting is thereby held constant, and the EDM process gradually erodes the surface of the workpiece. When enough metal has been removed to change the gap distance, the microprocessor senses this and signals the servo mechanism to advance the ram head to the proper gap distance and the process continues (Jameson, 1983) (Poco, 1993).

The power supply is solid state and is also microprocessor driven. The power supply or generator accepts alternating current and a rectifier changes the electricity to a pulsating direct current. One lead of the power supply is connected to the workpiece, which is immersed in a work tank filled with dielectric oil. The work tank is connected to a dielectric pump, a dielectric reservoir and a filter system. The pump provides the pressure for flushing the work area and moving the oil while the filter removes and traps debris and metal particles in the filter. The dielectric reservoir stores surplus oil and provides a container for draining the oil from the work tank between operations (Kubistant, 1993).

In the EDM process, multiple variables affect the accuracy and efficiency of machining as well as the metal removal rate and surface finish of the workpiece and the electrode. Control of these variables is fundamental to optimizing the success of any machining operation (Guitrau, 1993) (Jameson, 1993). The basic settings of the EDM unit are polarity, peak current, average current on-time, off-time; frequency, and duty cycle. Polarity refers to an electrical condition determining the direction of the current flow in relation to the electrode. Generally a positive electrode results in lower electrode wear, slower metal removal rates and better surface finishes, while a negative electrode will produce greater electrode wear, faster metal removal rates and rougher surface finishes (Walker, 1993). Amperage represents the total electrical energy or cutting power that is produced by the power supply and will determine the cutting rate (Poco 1993). A higher amperage setting will consequently result in a faster metal removal rate, greater electrode wear, and a rougher surface finish. A lower amperage setting will result in a slower metal removal rate, less electrode wear, and a finer surface finish.

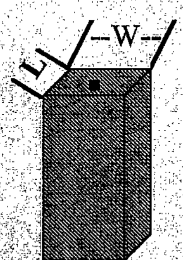
Guitrau (1993) and Poco (1993) recommended that the maximum amperage use should be determined by the electrode frontal surface (Figure 9). The maximum recommended amperage is the product of the electrode frontal area in square inches (in^2) multiplied by 65 amps. The on-time, also known as the pulse time, is the duration or time that energy is sustained over the workpiece in microseconds. A long on-time will provide a high metal removal rate, low electrode wear, and a rough finish. Conversely, a short on-time will give a low metal removal rate, higher electrode wear, and a finer finish. The off-time, or pause time will affect the speed and stability of the cut. However, a very short off-time will not allow the ejected particles of the workpiece to be flushed away, creating an unstable spark and cutting conditions with possible damage to the workpiece and electrode due to arcing. Total cycle time is the sum of the on-time and the off-time, measured in microseconds. The duty cycle is the on-time divided by the sum of the on-time and the off-time. The frequency is the number of cycles produced within the gap in one second, and it will be equal to one thousand divided by the total cycle time in microseconds. A low duty cycle and higher frequency will give a low metal removal rate and a fine surface finish, while a high duty cycle and lower frequency will give a high metal removal rate and a rougher surface finish. Flushing removes particles from the gap, which helps to prevent arcing, maintain stable cutting conditions, reduce electrode wear and reduce overcut (Jameson 1983). Overcut is the result of discharges occurring at the closest point between the lateral sides of the electrode and the workpiece. Overcut could be considered a negative outcome, but can be controlled by reducing the amperage, reducing the gap distance, and maintaining a stable cutting condition (Figure 10).

Figure 9: Diagram and formula of maximum recommended amperage related to electrode frontal area.

Maximum Amperage

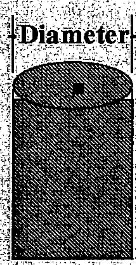
Max. Amp. = Electrode frontal area x 50

(Area in square inches)



Electrode frontal area = Length x Width *

Area = L x W

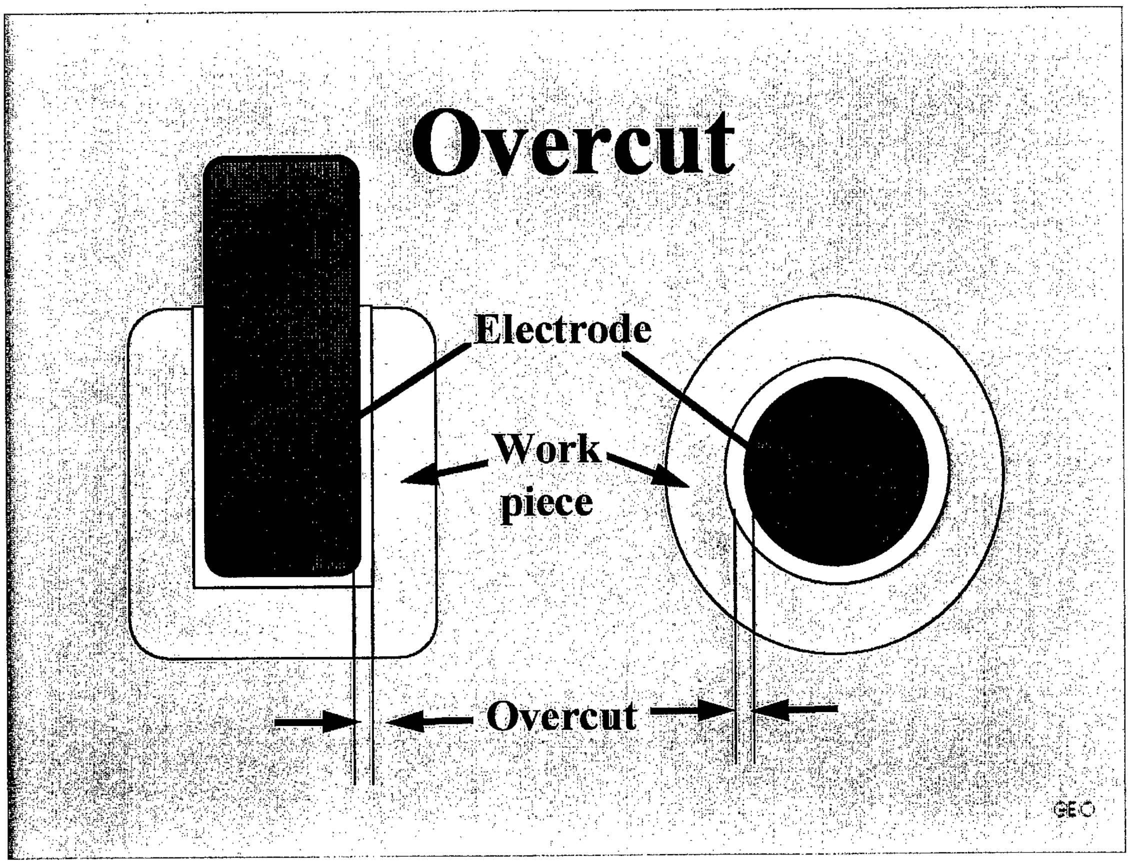


Electrode frontal area = Radius^2 x 3.14 *

Radius = 1/2 Diameter

** Minus area of flushing hole*

Figure 10: Overcut is the result of discharges occurring at the closest point between the lateral sides and end of the electrode and the workpiece. Is the difference between the workpiece cavity and the electrode size.


Overcut
Electrode
Work
piece
Overcut
GEO

Electrode wear is a very important parameter to control. The higher the electrode wear, the greater the inaccuracy of the resulting end product,

because the shape of the electrode is altered.. According to Hansvedt (1992) and Poco (1993), it is possible to establish a cut in which the wear of the electrode is kept to a minimum with a technique known as the no-wear mode. The no-wear mode can be accomplished by producing a pulse of sufficient length to permit a slight plating of particles from the workpiece onto the electrode. The plating reaction occurs by reducing the flushing flow to a minimum, and by maintaining a uniform temperature at the arc gap. No-wear is affected by the on-time, amperage, gap distance, surface of the electrode, and flushing. It can be obtained only in the pulse mode using positive polarity. Controlling all the parameters to obtain minimum electrode wear is very important when accuracy or precision is one of the main goals of the EDM operation.

O. EDM in Dentistry

The first documented use of EDM in dentistry was by Rubeling and Kreylos(1982). They described different applications of EDM, and believed its use and development in dentistry would increase because of casting discrepancies associated with the use of non-noble alloys. Misch (1993) stated that precious metal shrinkage is approximately1.5%, while non-precious metal shrinkage approaches 3.0%. Sillard (1992a) and Misch (1993) recommended to avoid the use of non-precious alloys for implant castings to prevent galvanic reactions, and because soldering non-precious metal is more technique sensitive. Rubelling and Kreylos observed that EDM is used in industry for precision drilling, to perforate shapes and forms, as well as to create smooth surfaces with a great degree of accuracy. He recommended the use of EDM in dentistry for the addition of friction pins, extracoronal extensions, and precision attachments in non-precious metal fixed and removable prostheses.

Windeler (1982) received a patent for improving the fit of a crown or other type of cast prosthesis using EDM. His technique utilized a copper plated replica of the master die as the electrode. Homa *et al.* (1987) reported fit correction of non-precious metal dental castings using EDM and silver plated dies as electrodes. The process was limited primarily by the precision of the silver plated die and EDM overcut, and secondarily by the precision of orientation of the die to the casting.

Andersson *et al.* (1989) found that precision casting of titanium was very difficult and developed a system for the fabrication of unalloyed titanium crown and bridges. This technique machines a dental prosthesis from a solid piece of titanium. The cameo surface is formed by a coping milling machine and the intaglio surface is formed with the EDM process. For the EDM electrode preparation, the stone die is placed in a machine equipped for carbon milling. This machine prepares carbon replicas of the die that are used as electrodes. Bergman et al (1990), did a two year recall study of the titanium crowns of Andersson et al 1989 and concluded that marginal integrity remained excellent to satisfactory. In 1992 the Procera™ System (Nobelpharma Company Götherborg, Sweden) was introduced. This system was used to fabricate porcelain-titanium crowns with the same copy milling and EDM technique developed by Andersson.

Sillard (1990) received a patent for using EDM in the fabrication of a "fixed removable dental implant system." This system is used primarily for implant overdenture cases. Sillard (1992a) described his patented method that consisted of a substructure bar that is connected to the implants, and a removable superstructure that is machined with the EDM until a completely passive fit to the substructure bar is achieved After machining, the removable metal superstructure is incorporated into the prosthesis. Sillard (1992b) noted that during the machining process, the polarity is reversed occasionally to share the metal removal and electrode wear between the two parts. By using this technique he stated that 100% accuracy between segments is achieved, with a minimal overcut and a very fine finish. It is the precision fit of these two metal components of the bar that provides the retention. His prosthesis fabrication technique included the addition of guide pins and a locking mechanism, also precisely machined with EDM. Although the prosthesis fits very accurately and retentively, the fit of the implant substructure bar to the implants is not addressed.

Van Roekel (1992b) stated that the fixed removable concept was not new to the dental profession, with the Bennett blade (1915 and 1920), representing the first attempt to use a precision fit between a substructure bar and removable metal superstructure of a tooth supported restoration. According to Mensor (1980), other variation of tooth supported fixed removable restorations have been developed by Hader, Dolder and Baker.

Various authors have reported different cases of fixed removable prostheses using Sillard's concept of using the EDM process to machine a removable superstructure to an implant retained substructure. Fisher and Rubeling (1990), reported the fabrication of an implant borne removable partial denture using EDM. They used EDM to precisely machine parallel surfaces between a secondary superstructure and a primary cast framework. In this system, the secondary portion can be removed by the patient by opening a bolt. Van Roekel (1992b) modified the Sillard's technique by adding friction pins, while Finger *et al.* (1992), Lefkove and Beals (1992), Charles and Lefkove (1992), and Ganz (1995) added swing latch attachments in addition to the friction pins to improve retention. Finger *et al.* (1992) stated that the retention and stability of these EDM frameworks were superior to that of a bar and clip retained overdenture, such as the Hader and Dolder bar systems.

Probster *et al.* (1991) fabricated custom made resin bonded attachments using the EDM technique. The attachments were bonded to the abutments and were used to support a removable partial denture. Weber and Frank (1993) reported that the EDM process can overcome the problems associated with casting inaccuracies and dimensional changes of base metal alloys. He recognized that some of the advantages of using base metal alloys are high strength, lower cost, and low thermal conductivity. He described fixed and removable partial dentures using precision attachment and telescopic procedures fabricated with the EDM process.

Boening *et al.* (1992) evaluated the accuracy of fit of the Procera system. According to Boening, the Procera system demonstrated remarkable accuracy when a chamfer or feather edge preparation was used, but discrepancies in the range of 290-750μm were observed in shoulder preparations. Leong *et al.* (1994), evaluated the marginal fit of cast noble alloy crowns, cast titanium crowns, and machine-milled (Procera™) crowns. His study did not find significant difference between the marginal discrepancy of machine-milled crowns (60 μm) and cast titanium crowns (54 μm). The noble alloy crowns showed the smallest mean marginal opening (25 μm). Sjogren *et al.* (1988), stated that unalloyed titanium has proven to be the most successful material in implant dentistry, and recommended precision mechanical machining combined with spark erosion to produce an unalloyed titanium framework.

Van Roekel (1992a) provided a brief history on the EDM process and its use in dentistry and discussed the numerous advantages offered by the EDM process. The EDM process is not affected by metal hardness since it is a thermal process. EDM can be used to machine small thin objects without distortion. It is not affected by the adhesive characteristic of the workpiece because there is no contact between the electrode and the workpiece. EDM also provides a smooth burr-free surface with accuracy to within 0.0001 in.

Linehan and Windeler (1994) investigated the use of EDM to correct casting discrepancies and distortions in dental reconstruction of osseointegrated dental implant prostheses. They concluded that the electric discharge machining technique provides a simple, fast and accurate method for the correction of casting inaccuracies. Linehan noted that the mean fit of four of the five implant frameworks in his study were improved after machining. He also noted that the frameworks did not fit the model as passively as they fit the master cast used as an electrode. He observed that the no-wear mode of the electrode was not achieved, with 40% electrode wear. One of the major factors affecting the EDM process when correcting framework inaccuracies is preservation of an accurate electrode.

The technique described by Linehan and Windeler may also be considered in those instances where the superstructure for an implant prosthesis had an initial passive fit and is subsequently distorted by porcelain or acrylic addition, as indicated by Davis *et al.* (1988), Weiner (1992), and Misch (1993). Processed methyl metacrylate shrinks approximately 7% in volume. This is an important consideration when a bulk of acrylic resin is used in processing denture teeth and base to a cast metal superstructure. The acrylic shrinkage can affect the passive fit of the metal. Porcelain shrinkage of approximately 20% occurs during the firing process and may also distort the metal superstructure (Marshall *et al.* 1994). EDM may be used to correct discrepancies that occur after porcelain or acrylic resin application because the process does not generate or transmit any heat to the workpiece outside the gap area.

Schmitt *et al.* (1995) and Schmitt and Chance (1996) described a technique to improve the fit of implant cast restorations using copper analogs of the implants as electrodes and the EDM process. Schmitt and Chance (1995) described a process whereby the exterior as well as the interior of an implant retained restorations was formed from a solid block of titanium with EDM.

Weimer (1988) noted that the exact pulse duration must be determined by the physical characteristic of the workpiece and electrode material. He also stated that the amount of electrode wear must be minimized and that by controlling the current pulse, amperage, on-time and duty cycle, the amount of metal that is vaporized and melted can be controlled. Excessively long on-time can create heat build up, causing the workpiece material to melt instead of vaporize which creates some negative effects on the surface integrity and surface finish.

As previously discussed, multiple parameters affect the finish and accuracy of the prosthesis when using electric discharge machining. It is imperative that those factors be understood and accurately adjusted to obtain an accurate product with an optimal efficient metal removal rate, a smooth surface finish and maximal electrode material preservation.

III. OBJECTIVES AND HYPOTHESES

The objectives of this study were to investigate how changes in amperage and on-time of the EDM process affect the metal removal rate (MRR) and surface finish (Ra) of representative dental materials and the end wear of electrode materials in different metal-electrode combinations. An additional objective of this investigation was to create initial machining parameters and guides for the use of EDM in dentistry. These parameters are intended to enhance the use of EDM to improve the fitting of dental castings and other dental applications.

Two hypotheses were tested in this investigation;

1) Metal removal rate and surface finish of representative dental alloys are affected by changes in amperage, on-time, and electrode composition.

2) Wear of different electrode materials are affected by amperage, on-time, and representative dental alloys.

Two Null hypotheses were tested in this investigation;

1) Metal removal rate and surface finish of representative dental alloys are not affected by changes in amperage, on-time, and electrode composition.

2) Wear of different electrode materials are not affected by amperage, on-time, and representative dental alloys.

IV. MATERIALS AND METHODS

A. Electrode Selection

The purpose of any material used as an electrode in the EDM process is to transmit the electrical machining impulses, allowing the workpiece erosion to take place, with minimal or no self erosion. There are five key factors in electrode material selection. These performance factors are metal removal rate, surface finish, wear, machinability and material cost. It is known in fact that electrode materials differ in performance depending on the application and workpiece material. According to Poco (1993), the five most commonly used electrode materials are graphite, copper, brass, zinc, and tungsten. Graphite is a nonmetallic material usually classified as a metalloid, because it exhibits characteristics representative of both metals and nonmetals. Graphite possesses a very high sublimation temperature transforming from a solid to a gaseous state without becoming a liquid. Good electrical and thermal properties, along with its machinability, makes graphite an excellent electrode material. Graphite is classified according to particle size (see table 1). Ansgtrofine is less than 1 micron, ultrafine 1-5 microns, superfine 6-10 microns, fine 11-20 microns, medium 21-100 microns, and coarse more than 100 microns. Coarse graphite is not suitable for EDM purposes. The small particle size graphite electrodes (less than 5 microns) produce better surface finish and good wear resistance. For dental applications only graphite of 5 or less microns should be considered.

Table 1: Graphite Classification ACCORDING TO PARTICLE SIZE in Microns (μ)	
Class	Particle Size
Ansgtrofine	Less than I μ
Ultrafine	1-5 μ
Superfine	6-10 μ
Fine	11-20 μ
Medium	21-100 μ
Coarse	More than 100 μ

Brass, zinc, and copper, are easily obtainable, consistent in quality, and low in cost. But they have their drawbacks as well. Brass and zinc have a very high electrode wear ratio due to low melting points. Copper is very difficult to machine. Tungsten, in theory is the best of the metals for use as an electrode. Pure tungsten has very high strength, density, hardness and a high melting point, but it is expensive and very difficult to machine. However, if tungsten is combined with a more ductile material such as copper, the resulting material is easier to machine as well as extremely strong and wear resistant.

Three different electrode materials were selected for this study. The following are the electrode materials and their characteristics:

1) AF-5 graphite, (Poco Graphite Ind.): AF-5 is the only graphite electrode material available on the market with an average particle size of less than one micron (Ansgtrofine). This particle structure gives AF-5 superior strength, excellent metal removal rate, fine surface finish, very high wear resistance, and excellent machinability (Poco 1993).

2) Copper-graphite C-3 (Poco Graphite Ind.): C-3 is a high density graphite infiltrated with copper, with a particle size of less than 5 microns. C-3 is recommended when speed, wear and surface finish are important. According to Poco (1993), C-3 is a possible alternative when poor flushing conditions exist. It offers better rigidity for fragile electrode fabrication and excellent machinability, but has lowest cutting rate and a higher wear rate than AF-5 graphite.

3) Precision Copper Tube (Saturn Ind.): Copper produces a better surface finish than graphite and copper graphite. It has a lower metal removal rate, and lower electrode wear than graphite, but its main disadvantage is that it is very difficult to machine (Poco, 1993).

A major advantage of graphite and copper-graphite electrodes is that they are easy to machine into small and detailed shapes, which is difficult to achieve with copper electrodes (Hansvedt 1992).

B. Electrode fabrication

All electrodes were fabricated into a standard shape. (An overall diameter of 4.7 mm., a central flush hole of 0.5 mm. and a total length of 101 mm) The electrode diameter approximates the size of gold cylinders and transmucosal abutments used in implant dentistry. Graphite (AF-5) and Copper Graphite (C-3), provided by Poco Graphite Industries, and were machined to desired specifications by Saturn Industries, Hudson, NY.

Due to the poor machinability of copper, it was impossible to drill a 0.5 mm flushing hole through the solid copper electrode. To maintain the standard shape of all electrodes used in this investigation, three precision copper tubes with standarized internal and external diameters were press fitted together (a tube within a tube) to obtained the desired dimension of 4.7 mm external diameter with a flushing hole diameter of 0.5 mm., (Table 2).

Table 2: Precision copper tubes diameters.		
Tube Position	External diameter	Internal diameter
External Tube	4.7 mm.	2.92 mm.
Middle Tube	2.92 mm.	1.35 mm.
InternalTube	1.35 mm.	0.50 mm.
Tubes were press fitted to obtained the desired electrode diameter.		

C. Workpiece selection

Three representative dental metals were used: Type III gold (Ney), Olympia ceramo-metal alloy (Jelenko) and Titanium (Rematitan). The selection criteria for Type III gold and Olympia ceramo-metal alloy was based on their high utilization in conventional prosthodontics and implant dentistry (Misch 1993). Titanium was selected due to its biocompatibility and increased use in implant dentistry, (Gross, 1988) (Kasemo, 1983).

D. Workpiece fabrication

Twenty square acrylic bars 6 mm x 6 mm x 32 mm length were prepared. The bars were sprued indirectly using three 6 gauge sprues. A wax bar 6 mm in diameter and 32 mm in length acted as a reservoir and was positioned near the heat center of the investing ring. Four 10 gauge wax patterns were placed on the lateral surfaces of the bar as casting aides Ten bars were invested in Beauty Cast (Whip Mix Corp., Louisville, Kentucky) for the casting of the Type III gold bars and ten in Ceramigold (Whip Mix, Louisville, Kentucky) for the casting ceramo-metal alloy bars. The gold bars were cast using a gas-air flame and the ceramo-metal alloy bars using a gas-oxygen flame. Conventional casting techniques, manufacturer specifications and a centrifugal casting machine were used for the casting of the workpieces. Castings were allowed to bench cool, removed from the investment and sprues cut. All cast bars were machined to uniform dimensions of 5.7 mm x 5.7 mm x x 31 mm length at Brooks AFB, Texas machine shop (Figure11). Five tests were performed on the top and bottom side of each bar for a total of ten tests per bar.

Titanium ingots (Rematitan, Dentarium Co., Newtown, PA) as provided by the manufacturer were used as workpieces. Each ingot measured 13 mm height x 22 mm diameter. Nine tests were performed on each ingot using only the surface that was not engraved with the manufacturer's name (Figure 12). Wet silicon carbide sandpaper was used to prepare and standardize the machining surfaces of the ingots. Surfaces were sanded sequentially 400, 600, and 1000 grit silicon carbide paper.

E. Machining Parameters

1. Polarity

The EDM process is based on the assignment of polarity, either positive or negative, to the electrode and the workpiece. The ionization of particles through the dielectric fluid results in a flow of current and subsequent generation of heat in the discharge channel. Positive polarity focuses the heat and vaporization towards the workpiece and away from the electrode. This serves to minimize the amount of electrode wear. Because accuracy is absolutely important in dental applications, minimal electrode wear is desired. To enhance the accuracy, positive polarity was selected for nine of the eleven metal-electrode combinations. The metallurgical industry recommends machining Ti using negative polarity due to its low MRR when positive polarity is used.

Figure 11. AF-5 electrode / Type 3 Gold bar workpiece, after the EDM process.

(Total of 5 cavities were machined on each top and bottom surfaces)

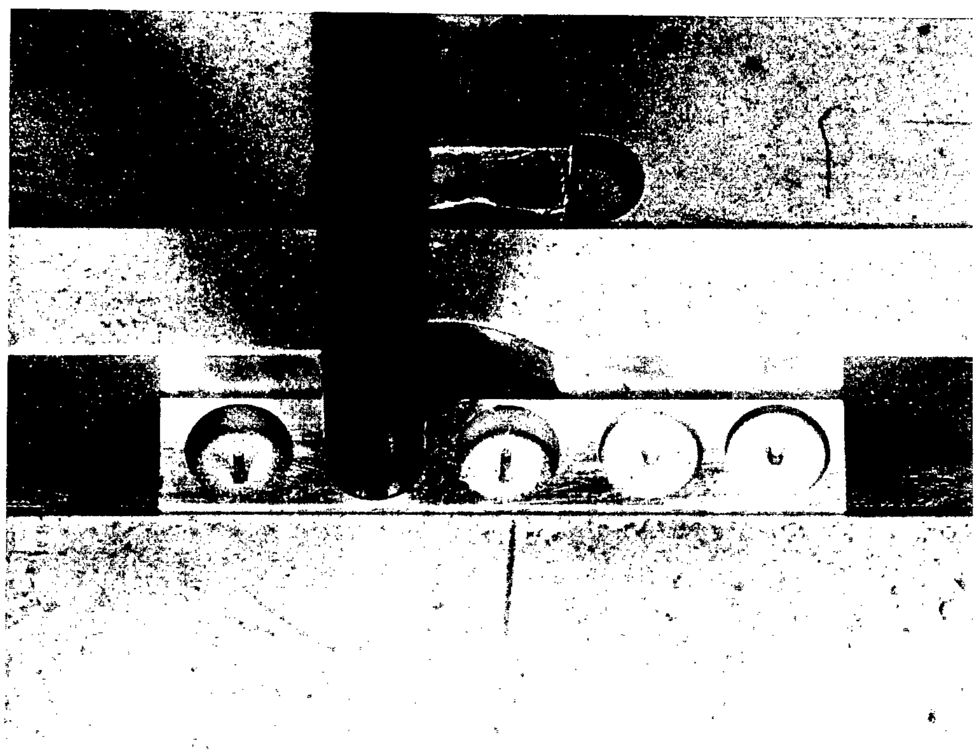
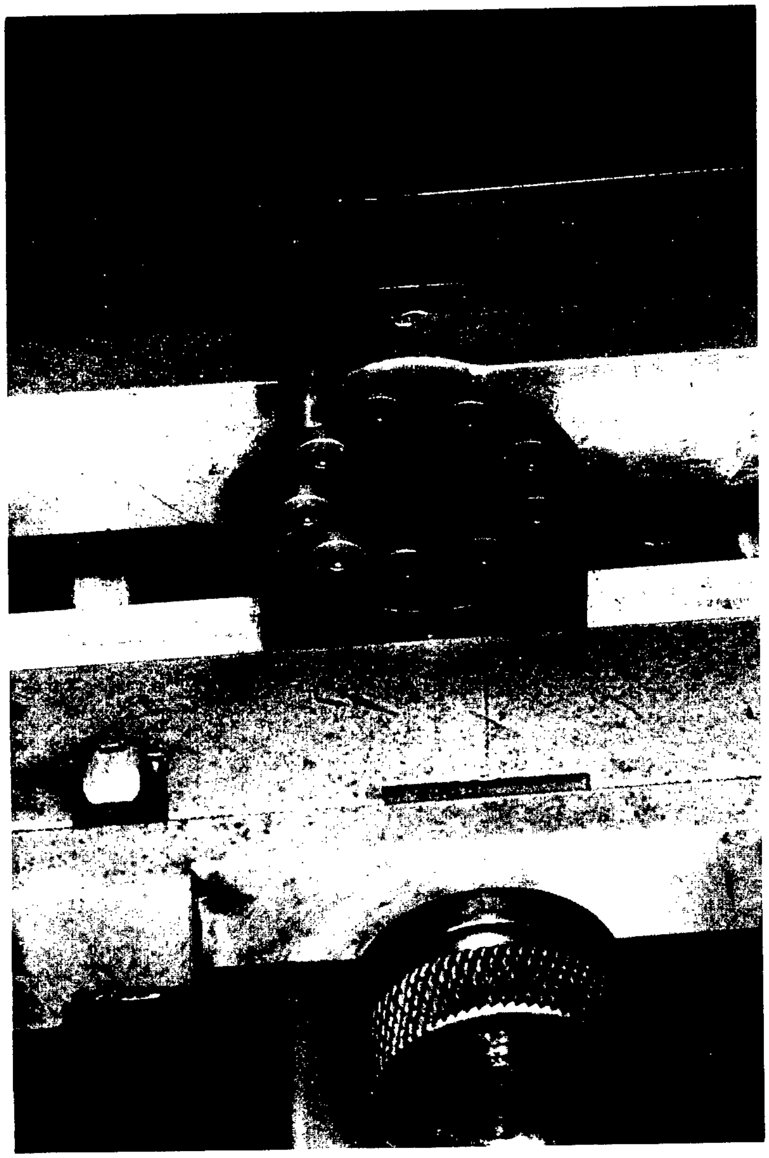


Figure 12. Copper electrode / Titanium ingot workpiece, after EDM process.

(9 cavities were machined on the top surface of each Ti ingot)



Ti workpiece with AF-5 and C-3 electrodes combinations using reverse or negative polarity were also tested in this investigation. Negative polarity was not considered using a copper electrode due to its low meting point, which can result in high electrode wear and no metal removal rate.

2. EDM Cycle

Each cycle has an on-time and off-time that is expressed in micro-seconds. (μSec) Since all the work is done during the on-time, the duration of these pulses and the number of cycles per second (frequency) are important. Normally a high frequency cycle will provide a better finish and a lower MRR, (Poco 1993). Metal removal rate is directly proportional to the amount of energy applied during the on-time. This energy is controlled by the peak amperage and the length of the on-time. The longer the on-time is sustained the more workpiece material will be removed, resulting in deeper, broader cuts with a rougher surface finish. Excessive on-times can be counter productive. When the optimum on-time for each electrode material/workmetal combinations is exceeded, the MRR actually starts decreasing. Poco (1993) and Hansvedt (1992) reported performance charts for different industrial metal-electrode combinations showed that the ideal maximum on-time ranged from 32 to 50 μSec. A benefit of long on-times is that the electrode can be placed in a minimal wear situation. A shorter on-time will then provide a slower MRR, a better surface finish, and more electrode wear. The off-time is also known as the pause time and is required for the re-ionization of the dielectric fluid. Dielectric fluid cools the electrode and the workpiece and cleans away the eroded particles of the workpiece material from the gap area. The off time affects the speed and stability of the cut, but it does not affect the surface finish, electrode wear, or the metal removal. The relation of the on-time and the off-time is the measure of efficiency, better known as the % duty cycle, (Poco, 1993).

$$\text{Total Cycle Time } (\mu\text{Sec}) = \text{On-Time} + \text{Off-Time}$$

$$\%\ \text{Duty Cycle} = \text{On-Time} / (\text{Total Cycle Time}) \times 100$$

$$\text{Frequency (kHz)} = 1000 / \text{Total Cycle Time } (\mu\text{Sec})$$

The on-times selected for this investigation were 4.0, 25.6 and 51.2 μSec. A constant duty cycle of 60 % was selected for all tests. The Hansvedt EDM machine Model 201 adjusts the off time automatically to allow more stable, efficient, and reliable machining conditions. For a 60% duty cycle with on-times of 4.0, 25.6, and 51.2 μsec, the following off times and frequency values were obtained;

a) 4.0 on-time

60 % duty cycle = 4.0 / (4.0 + off-time)

off time = 2.67 μSec

Frequency = 1000 / (4.00 + 2.67) = 1000 / 6.67 = 149.9 kHz

b) 25.60 on-time

60% duty cycle = 25.6 / (25.6 + off-time)

off-time = 17.00 μSec

Frequency = 1000/ (25.6 + 17.00) = 1000 / 42.6 = 23.47 kHz

c) 51.20 0n-time

60% duty cycle = 51.2 / (51.2 + off time)

off-time = 34.13 μSec

Frequency = 1000 / (51.2 + 34.13) = 1000/ 86.33 = 11.58 kHz

3. Amperage

The amount of power used in EDM is measured in units of amperage. The size and shape of the finished electrode is important to determine the maximum peak amperage (I_p) that can be utilized. A recommended safe guideline is 65 amps per square inch (Hansvedt, 1992). Excessive amperage can cause instability and DC arcing in the cut. Also when using maximum amperages, the spark gap can be quite large and smaller details may have to be omitted from the electrode, the finer details can be obtained at a second machining session using less power and a new electrode. Small electrodes can be easily damaged by excessive amperage. Average current (A) is the average of the amperage in the spark gap measured over the complete cycle. It can be calculated by multiplying the duty cycle by the peak current. Average current is an indication of machining operation efficiency with respect to MRR (Guitrau, 1993).

Electrode Frontal Area = $(1/2 \text{ diameter})^2(\pi) = \text{Radius}^2 \times 3.14$

Electrode Area = $[(1/2)(4.75)]^2(\pi) = (2.37)^2(\pi) = (5.64)(3.14) = 17.70\ \text{mm}^2$

$$\text{Flushing Hole Area} = [(1/2)(0.5)]^2 (\pi) = (0.25)^2(\pi) = (0.0625)(3.14) = 0.196 \text{ mm}^2$$

$$\text{Electrode Frontal Area} = 17.70 \text{ mm}^2 - 0.196 \text{ mm}^2 = 17.504 \text{ mm}^2 = 0.0271 \text{ in}^2$$

$$I_p \text{ (max)} = \text{Electrode Frontal Area (in}^2) \times 65 \text{ (amps / in}^2)$$

$$I_P = 0.0271 \times 65 = 1.76 \text{ amp}$$

$$\text{Maximum average currents} = I_P \times \text{Duty Cycle\%}$$

$$\text{Max. Aver. currents} = 1.76\text{amp} \times 60\% = 1.05$$

To evaluate electrode-metal combination machining performance a peak current above, on and under the maximum recommended were selected The average currents or machining amperages selected for this investigations were 1.87, 0.936 and 0.468 amp. The average current were obtained by multiplying selected peak currents of 3.12, 1.56 and 0.78 amp by a constant duty cycle of 60%.

F. Test Procedure

In order to obtain general overall performance for each work metal-electrode combination the following procedure was followed. During each metal-electrode test series, the preset peak current or amperage was held constant with machining taking place at three on-time settings. Three replications at each on-time setting were performed. Three different amperages were tested for each metal-electrode combination. There was a total of nine metal-electrode combinations in positive polarity and two metal-electrode combinations in negative polarity (see table 3).

Table 3: Tests combinations										
Metal/Electrode Combination	Polarity	Aver. Amperage 0.468			Aver. Amperage 0.936			Aver. Amperage 1.872		
		on-time μ sec	on-time μ sec	on-time μ sec	on-time μ sec	on-time μ sec	on-time μ sec	on-time μ sec	on-time μ sec	on-time μ sec
Titanium /AF5	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Titanium / Copper	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Titanium / C3	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Olympia / AF5	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Olympia / Copper	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Olympia / C3	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Type III Gold /AF5	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Type III Gold / Copper	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Type III Gold / C3	(+)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Titanium /AF5	(-)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20
Titanium / C-3	(-)	4.00	25.60	51.20	4.00	25.60	51.20	4.00	25.60	51.20

Twenty-seven tests were made for each metal-electrode-polarity combination for a total of 297 tests. In each test, the off time was adjusted to maintain a 60% duty cycle. The servo mechanism control was set to maintain a constant average machining voltage of 37 volts. The electrode flushing pressure for all tests was 3-4 psi (Figure 13). Test duration or machining time was varied depending on the rate of metal removal. Poco (1993) demonstrated that a cavity of at least 0.15 mm was needed to ensure accurate measurement. Analysis of pilot study results indicated that some titanium positive polarity tests would take as long as two hours to get an acceptable cut while some titanium negative polarity tests would take only 15 minutes. Most of the gold and Olympia samples required only 30 minutes. These variations did not affected the results due to the fact that metal removal rate was calculated in cubic millimeters per hour (Figure 14).

G. Measuring Techniques

1. Metal Removal Rate

Metal removal rate (MRR), which is the volume of metal removed from a workpiece in a specific period of time, is often expressed as cubic millimeters per hour (in^3/hr).

$$MRR = \frac{\text{Electrode Area } (mm^2) \times \text{Depth of Cut } (mm)}{\text{Time of cut } (min)} \times 60 = (mm^3/hr)$$

Figure 13: C-3 electrode / Type 3 Gold bar workpiece, (dielectric fluid through electrode flushing hole)

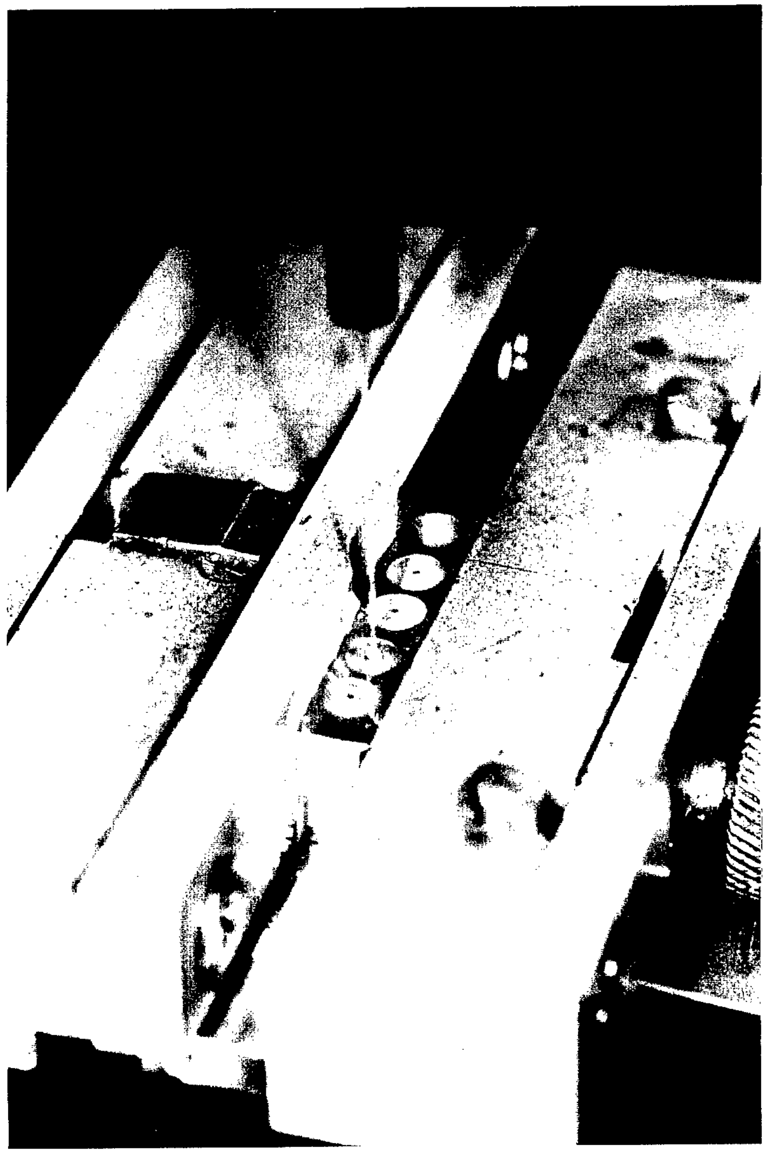
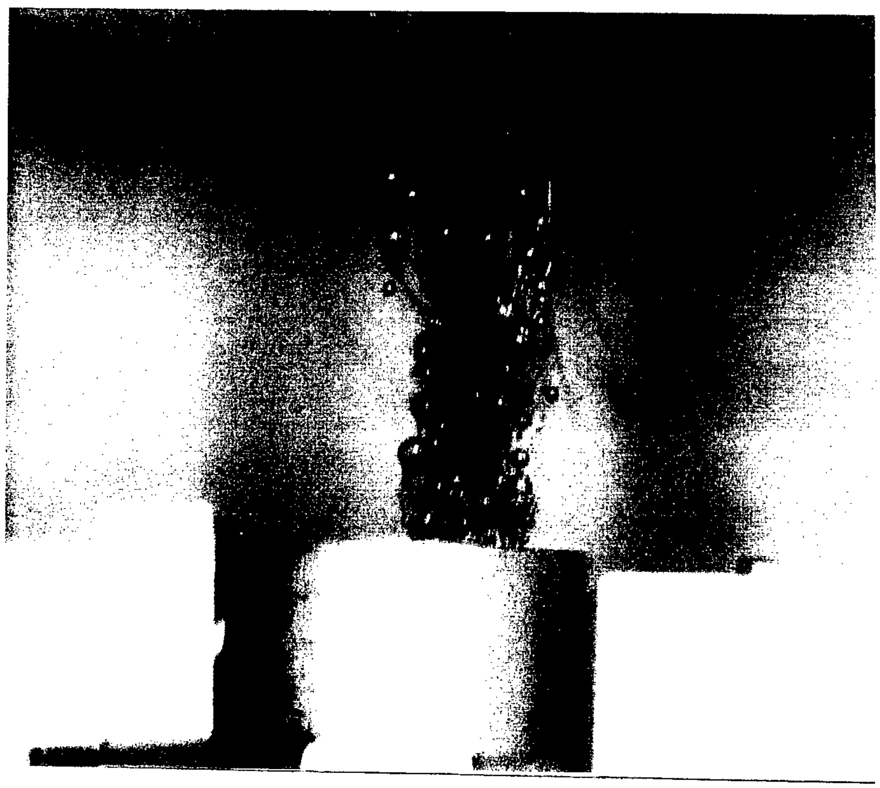


Figure 14 Af-5 electrode / Titanium ingot, during the EDM process - see the debris, and particles being expelled from the gap area.



To determine the volume of metal removed, the depth of each cut was measured with a depth micrometer in four different areas of the workpiece cavity. The average of these measurements provided the depth of the cut cavity in mm. A Digimatic Micrometer Indicator (Mituloyo Co., Japan) with an accuracy of 0.01 mm, was used for these measurements (figure 15).

The product of the depth of the cut and the frontal electrode area equalled the volume of metal removed in mm^3. Since a 0.5 mm flushing hole was used, it was necessary to subtract the area ($0.196mm^2$) of the hole from the total electrode area ($17.702\ mm^2$),to obtained the total electrode frontal area ($17.50\ mm^2$).

2. Surface Finish

Measurements of the finish of the eroded cavities were made using a surface analyzer or profilometer (Surfanalyzer System Model 4000, Federal Products Inc., Providence, Rhode Island). Roughness average (R_a), measured in microns (μm), was chosen as the standard method for defining surface finish. R_a is the most common unit of surface roughness measurement in use today. It is presently accepted worldwide in the metallurgical industry. In R_a measurements a mean line is constructed based on peak to valley distances and then the surface roughness value is stated as the arithmetic average of the distances of all profile points on the mean line (Rhoades and Hone, 1993). A diamond stylus (Groove Bottom EPT-01041, Federal Products Inc.) for grooves or holes to depth of 7mm was used to measure the surface finish (figure 16).

Figure 15: Measurement the workpiece cut cavities using a depth micrometer (Digimatic Micrometer Indicator, Mitutoyo Co., Japan)

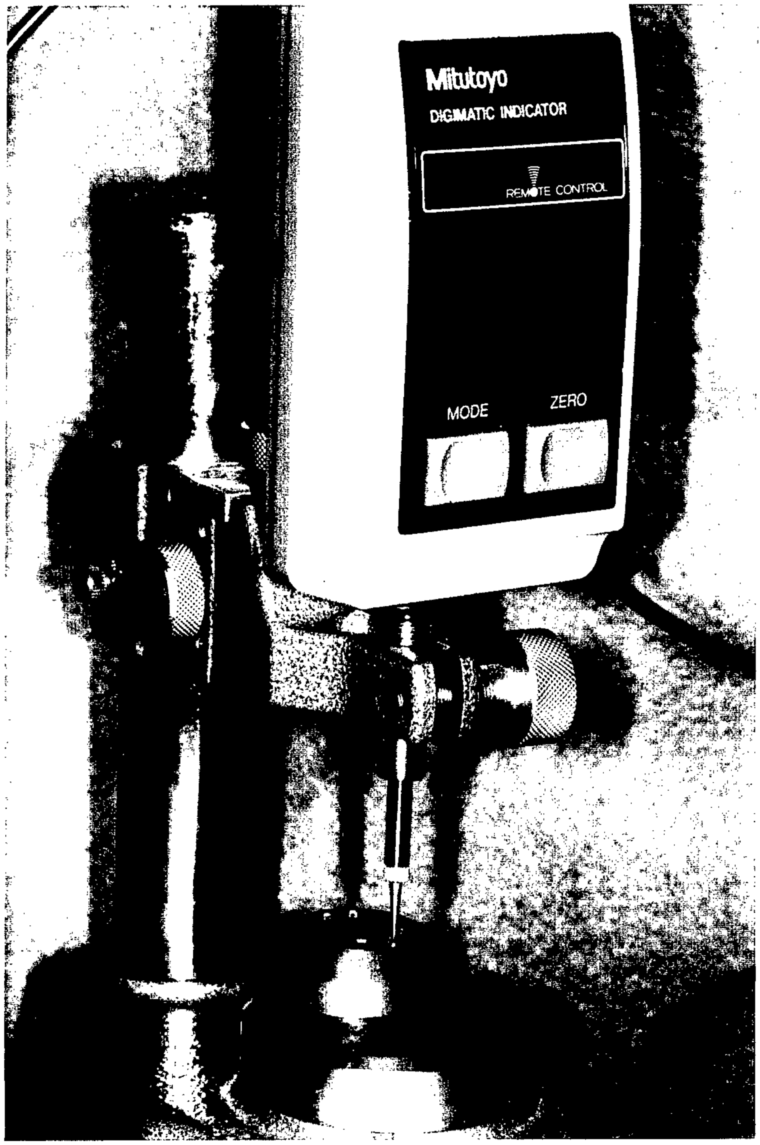
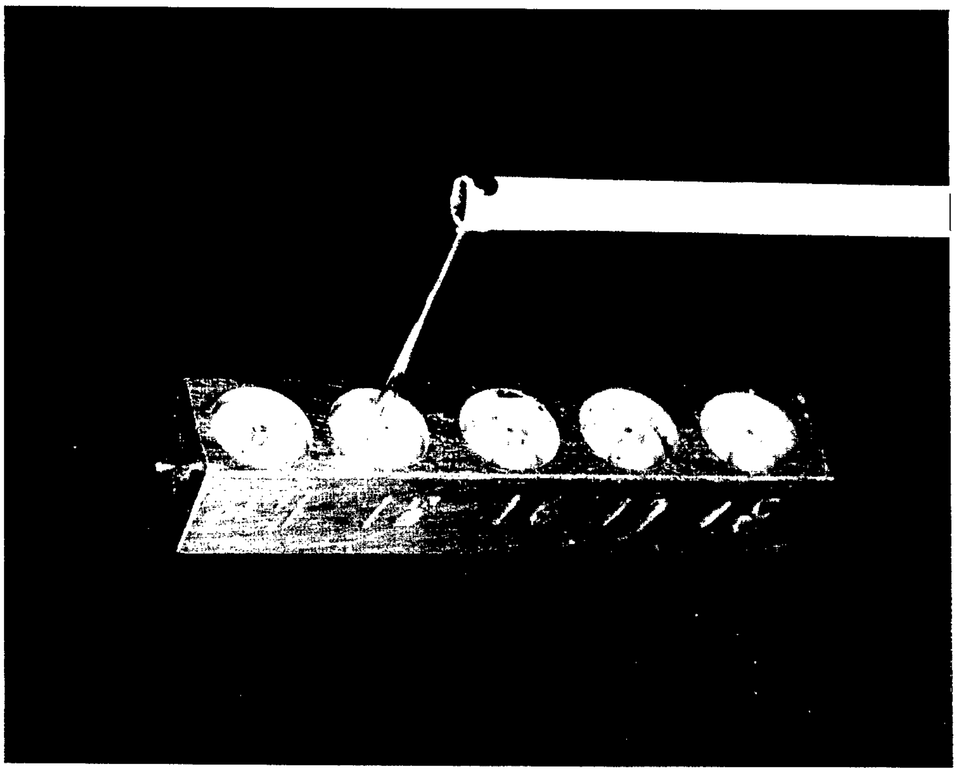

Mitutoyo
DIGIMATIC INDICATOR
REMOTE CONTROL
MODE
ZERO

Figure 16: Surface roughness (R_a) measurements of a Type 3 gold workpiece cavity. (Surfanylizer System Model 4000, Federal Products Inc,Providence, Rhode Island).

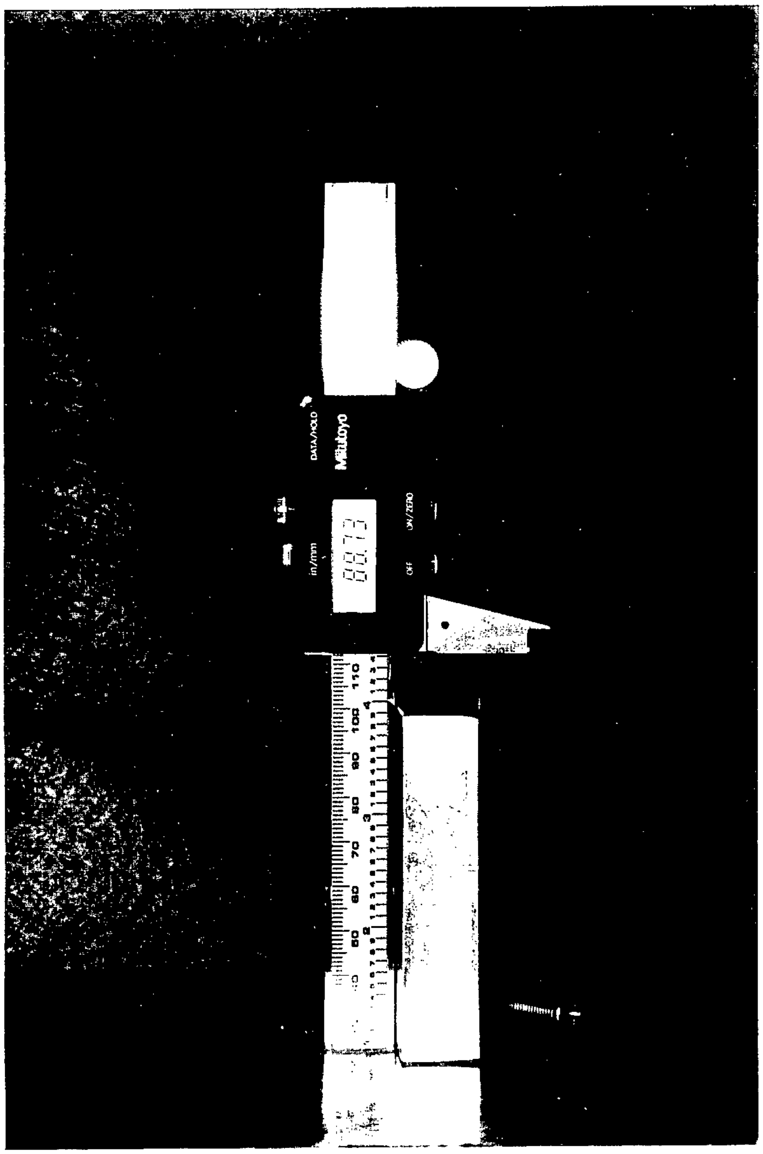


Three measurements of each cavity were made, with the average of these measurements used as the (R_a) The profilometer was calibrated before each measurement using a calibrating plate provided by Federal Products Inc. The profilometer test conditions were: cutoff = 0.8 mm, drive speed = 0.25 mm/sec, sample length 1 mm, traverse length = 0.95 mm. Light and scanning electron microscopy were used to produce a visual assessment of the surfaces.

3. Electrode Wear

End wear was measured in the following manner. Prior to each cut, the overall length of the electrode was measured and the reading recorded. After each cut, the electrode was then measured to determine the overall length. This length was then subtracted from the measurement made prior to the cut, with the remainder indicating the amount of end wear. An electronic vernier caliper (Mitutoyo Model DC-6, Japan), with an accuracy of 0.01 mm was used for these measurements. An aluminum block was fabricated (Brooks Air Force Base, machine shop) to accurately position the electrode for each measurement. (figure17) Redressing of the electrode was accomplished after each test so as to provide the same surface and finish for all measurements. A redressing aluminum block was fabricated for this purpose (Brooks Air Force Base, machine shop). This block held the electrode at a 90 degree angle to the sanding surface. Dry thousand grit waterproof silicon carbide sanding paper was used for this procedure. The sandpaper was attached to a glass plate over which the

Figure 17: Electrode length measurements were made before and after each test to determine the end wear of the electrode after each test. An electronic vernier caliper (Model DC-6, Mitutoyo Ind., Japan)


DATA/HOLD
Mitutoyo
in/mm
OFF
ON/ZERO

redressing block was passed to prepare a fresh electrode surface for the next test.The percentage of electrode wear (PEW) and the end wear ratio (EWR)) are more important figures than the actual electrode end wear, since it is a work/wear ratio. The PEW and EWR are a proportion of the amount of electrode wear in relation to the amount of workpiece material removed. The EWR can be measured by dividing the depth of the cut in the workpiece by the measured end wear of the electrode. PEW is calculated by dividing 100 by the EWR

H. Statistical Analysis and Data Management:

A spread sheet program (Microsoft Excel) was used in data collection. Comparisons were made between different levels of amperage and on-time. Factorial analysis of variance was applied to determine the statistical significance of the differences in the metal removal rate, surface finish and electrode wear. The significance level was 0.05 in all comparisons. Separate analyses was made to each metal-electrode combination. The statistical computation was performed with the use of SAS system, release 6.11.

V. RESULTS

Factorial analysis was applied to give statistical evaluation for MRR, surface finish and PEW. The analysis included the comparisons of different levels of amperage and on-time together with the test of statistical significance. Separate analyses were made for each metal-electrode combination.

A four-way ANOVA on electrode wear, metal removal rate and surface finish showed significant effects of metal, electrode material, amperage and on-time. The interaction of these factors were also highly significant. Significance level was the conventional five percent ($p \leq 0.05$).

All data means, values, and standard deviations of the calculated metal removal rate, surface finish, percentage of electrode wear (PEW), average cut and electrode end wear are contained in the Appendix. Vertical lines represent no significant difference between groups in relation to variations in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A; between 4.0 and 51.2 μSec = B, and between 25.6 and 51.2 μSec = C).

Figures 18 to 28 show the metal removal rate, surface finish and percentage of electrode wear for each metal/electrode combination, related to positive or negative polarity. Each table contains graphical information for MRR, surface finish and percentage of electrode wear for each metal/electrode/polarity combination in relation to amperages and on-times, allowing visual comparison of the performance of the different electrode /metal combinations used in this investigation in relation to the amperage and the on-time.

The results showed a highly significance difference in MRR, surface finish and PEW performance when different metals and polarities were used. Machining parameters and electrode materials performance showed minimal difference between the gold and Olympia samples. However, marked variability was observed between titanium positive polarity, titanium negative polarity and the gold / Olympia groups. Because of the marked difference in values, for graphical purposes, a different Y-scale was used for each group. Y-Scale values used were: gold and Olympia (MRR = 0-250 mm^3/hr; R_a 0-5 and PEW 0-50%); Titanium positive polarity (MRR = 0-20 mm^3/hr; R_a 0-12 and PEW 0-160%); Titanium negative polarity (MRR = 0-500 mm^3 /hr; R_a 0-7 and PEW 0-800%).

When considering changes in amperage, the results of this investigation showed that as amperage increased the MRR increased and, the surface finish became rougher (increase in R_a values) regardless of the metal-electrode combination, polarity, or on-time. However, changes in amperage did not consistently affected the PEW, with the exception of titanium negative polarity in which lower amperage produced more PEW than higher amperage.

When evaluating changes in the on-time, the results showed that the on-time significantly affected the MRR, surface finish, and the electrode wear of the different electrode-metal-polarity combinations when the amperage and all other variables remains unchanged. MRR's were higher for 25.6 μSec. and lowest for 4.0 μSec. on-times, with the exception of the titanium/AF-5 (+) polarity and the titanium/C-3 (-) polarity combinations in which MRR's were higher for 4.0 μSec. and lower for 51.2 μSec. on-times. Lower R_a values (better surface finish were obtained with lower on-times, except for titanium/c-3 (-) polarity and all the titanium (+) polarity groups in which R_a values were not in proportion to the on-time changes. PEW values were lower for 51.2 μSec. and higher for 4.0 μSec on-times for all combinations except for the titanium/AF-5 (+) polarity group which at a current of 0.936 A the 25.6 μSec on-time produces higher PEW than the 4.0 μSec and the titanium (-) polarity groups in where PEW were higher for the AF-5 group at 25.6 μSec and for the C-3 group at 51.2 μSec.

Because of the highly significance difference and variability between the different metals used in this investigation, the performance (MRR, R_a, PEW) results for each metal must be discussed individually. The overall performance of the metal-electrode combination is more important than an ideal or optimum value for only one of the machining parameters. An extremely high MRR with a high PEW and/or R_a is not considered a good performance. A high PEW (electrode wear) may predispose to lack of adaptation or accuracy of the final product due to the excessive wear and possible distortion of the electrode. A very rough surface (high R_a) is not acceptable for dental applications.

GOLD

Values as high as 205.85 mm^3/hr for MRR, as low as 0.589 R_a for surface finish, and 0.70% for PEW were obtained with the use of copper electrodes. The best overall performance for machining gold was obtained with the use of 0.468 A, on-time of 25.6

μSec and copper electrodes This combination produced a MRR of 36.651 mm^3/hr, a surface finish of 0.589 R_a, and a PEW of 1.29%. Other acceptable machining combinations were copper electrodes and 0.936 A with an on-time of 51.2 μSec, which produced a MRR of 49.782 mm^3/hr, a surface finish of 1.144 R_a and a PEW of 0.70%. or an on-time of 25.6 49μSec which produced a MRR of 64.770 mm^3/hr, a surface finish of 1.100 R_a and a PEW of 1.44%.

Other Amp/on-time combinations using AF-5 and C-3 electrodes produced surface finishes as low as 0.8 R_a's but with PEW's of 20-30% and MRR of less than half that obtained when using copper electrodes.

The best machining parameters for Gold were:

a) Copper electrodes.

b) Amperage below the maximum recommended for the surface area to be machined. For better surface finish decrease the Amp.

c) On-times 20-30 μSec (on-times from 30-50 μSec will reduce the PEW but will increase the R_a.).

OLYMPIA

The best overall performances for machining Olympia were obtained with the use of copper and AF-5 electrodes, amperages of 0.468 and 0.936 A , and on-times of 25.6 and 51.2 μSec. MRR values over 130 mm^3/hr were obtained with copper and C-3 electrodes, however, these tests produced PEW's over 5.0% and surface finishes over 2.0 R_a's. Best surface finishes were obtained with copper electrodes, currents of 0.468 A, and on-time of 4.0 and 25.6 μSec. However, PEW's of 9.41% and 2.07%

respectively were obtained. PEW of 0.00% (no wear) was obtained with AF-5 and copper electrodes with the following amperage / on-time combinations, AF-5 (0.468 A / 25.6 μSec and 0.936 A / 51.2μSec); copper (0.468 A / 51.2 μSec). Best machining parameters for MRR and PEW were obtained with the use of AF-5 and copper electrodes, 0.936 A, and on-times of 25.6-51.2 μSec. These combinations produced MRR,s of 35.45 to 49.57 mm^3/hr, PEW,s of 0.00 to 1.63% and surface finishes of 1.22 to 1.55 R_a's. Best finish machining parameters were obtained with copper and AF-5 electrodes, currents of 0.468 A and on-times between 4.0 to 25.6 μSec

The best machining parameters for Olympia were:

a) AF-5 and Copper electrodes

b) Amperage below the maximum recommended for the surface area to be machined. For better surface finishes decrease the Amp.

c) On-times between 25-50 μSec will reduced the PEW. Reducing the on-time slightly reduced the R_a but will increase the PEW.

TITANIUM (+) polarity

The best overall performances for machining titanium (+) polarity were obtained with the use of copper electrodes, amperage/on-time combinations of 0.468 A with on-times of 25.6 and 51.2 μSec. and 0.936 A with on-time of 51.2 μSec. These combinations produced MRR's between 2.68 to 1.55 mm^3/hr, PEW's of 0.00 to 1.48% and surface finishes of 0.64 to 1.84 R_a's. The best machining parameters for titanium (+) polarity were obtained with the use of copper electrodes, currents of 0.468 A and on-times of 51.2 μSec. This combination produced MRR of 1.55 mm^3/hr, a surface finish of 0.77 R_a and a PEW of 0.00%. Using the same combination but changing the on-time to 25.6 μSec, the MRR is slightly increased to 1.66 mm^3/hr and the surface finish improved to 0.64 R_a but the PEW slightly increased to 1.48%.

The best machining parameters for Titanium (+) polarity were:

a) Copper electrodes

b) Amperage below the maximum recommended for the surface area to be machined. For better surface finishes decrease the Amp.

c) On-times between 25-50 μSec. Reducing the on-time from 50 to 25 will Improve the finish with an approximate reduction of 0.15 on the R_a value.

c) Avoid low on-times. Low on-times produced severe electrode wear without improving the surface finish.

d) Avoid the use of AF-5 and/or C-3 electrodes. Use of AF-5 or C-3 produced high PEW values and showed severe deformation.

TITANIUM (-) polarity

The machining of titanium in negative polarity is used in the metallurgical industry to obtained high MRR while sacrificing electrode material and the quality of the surface finish. However, is not possible to machine titanium (-) polarity with copper electrodes due the electrical resistivity and conductivity of the metals. In this investigation, only AF-5 and C-3 electrodes were used for machining titanium (-) polarity. The best overall performances for both electrodes were produced with currents of 0.936 A and on-times of 4.0 μSec. Using this amperage/on-time combination, MRR's of 175.13 mm^3/hr, surface finishes of 1.86 R_a, and PEW's of 50.06 % were produced for AF-5 electrodes, and MRR's of 91.187 mm^3/hr, surface finishes of 1.97 R_a PEW's of 37.10 % were produced for C-3 electrodes.

Other results showed PEW values from 219.57 to 72184% when C-3 electrode and on-time of 51.2 μSec were used. Best PEW values (15.82 to 29.83%) for titanium (-) polarity were produced with AF-5 electrodes and on-time of 51.2 μSec, however these combinations also produced surface finishes between 2.85 to 6.80 R_a.

The best machining parameters for titanium(-) polarity were:

a) AF-5 or C-3 electrodes.

b) Amperage below the maximum recommended for the surface area to be machined.

c) Low on-times (different than when machining in positive polarity high on-times will severely affect and increase the PEW)

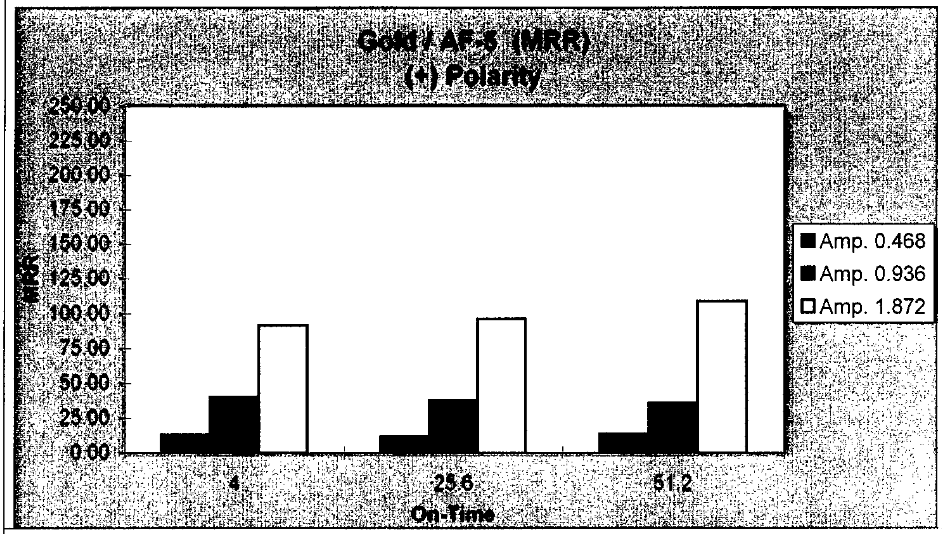
d) Use titanium negative polarity only for fast MRR, change to positive polarity to improve finish and adaptation of the workpiece.

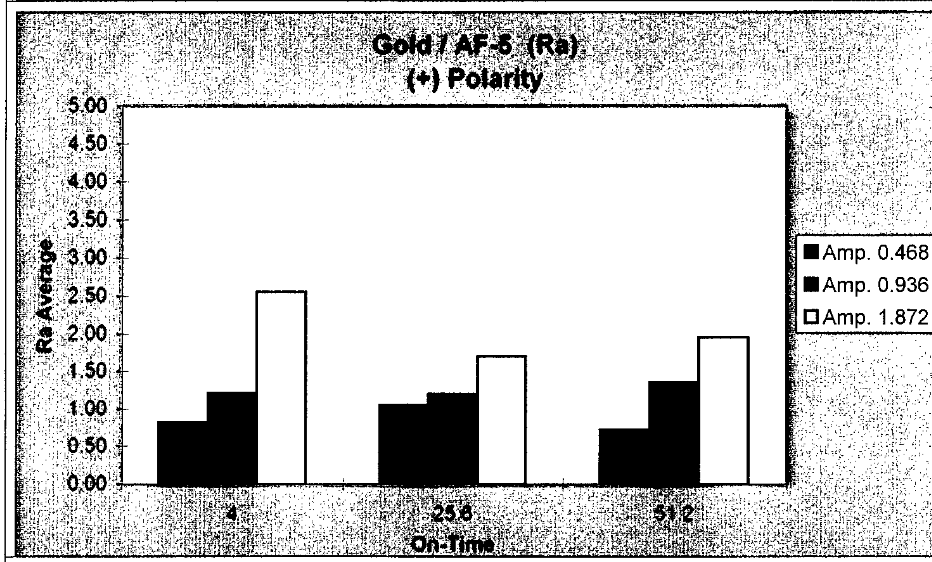
Figure 18: Gold / AF-5 (+) polarity

a) MRR

b) Surface Finish (R_a)

c) PEW


Gold / AF-5 (MRR)
(+) Polarity
MRR
250.00
225.00
200.00
175.00
150.00
125.00
100.00
75.00
50.00
25.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872


Gold / AF-5 (Ra)
(+) Polarity
Ra Average
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

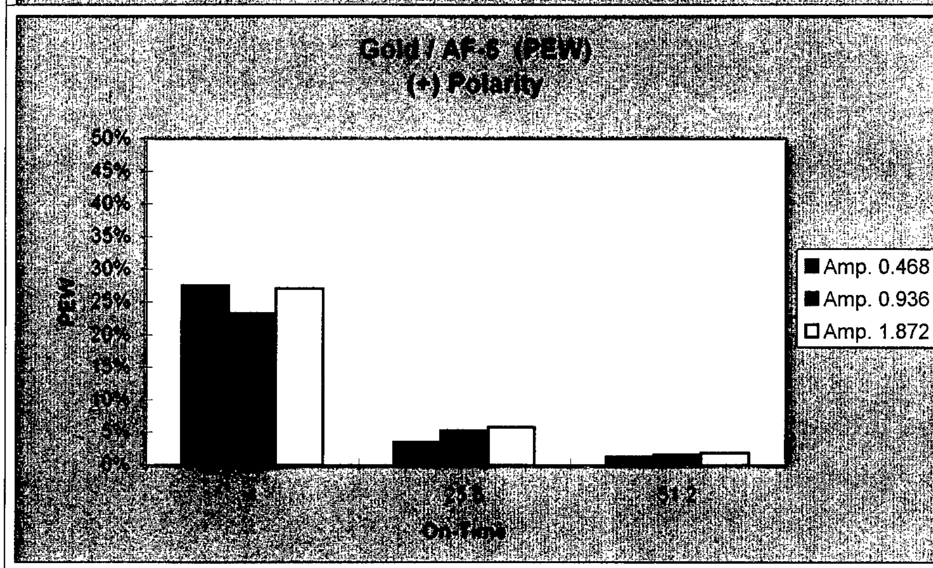
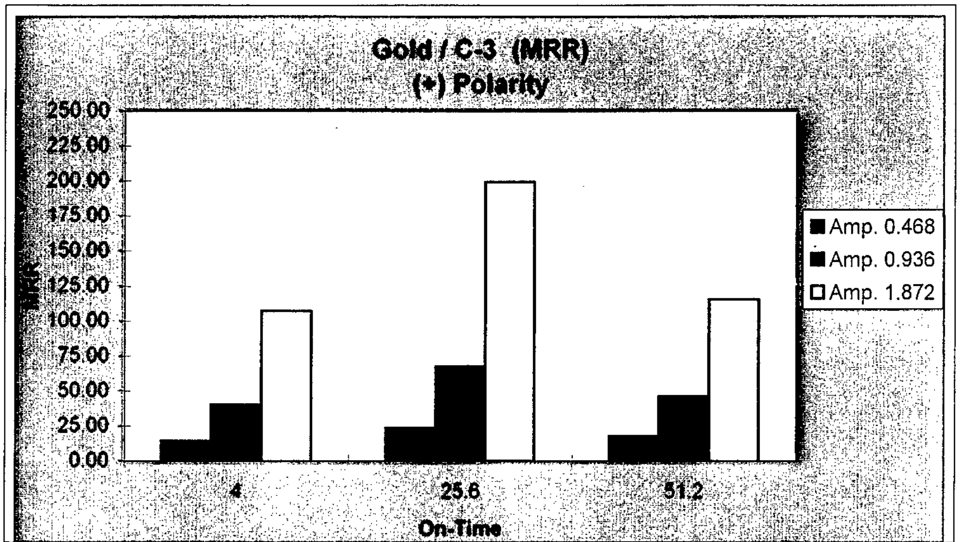

Gold / AF-5 (PEW)
(+) Polarity
PEW
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

Figure 19: Gold / C-3 (+) polarity

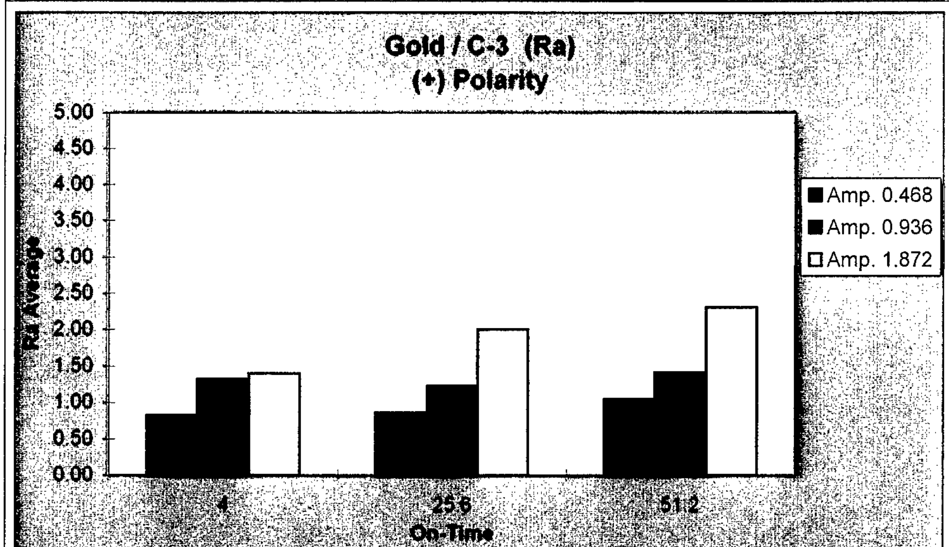
a) MRR

b) Surface Finish (R_a)

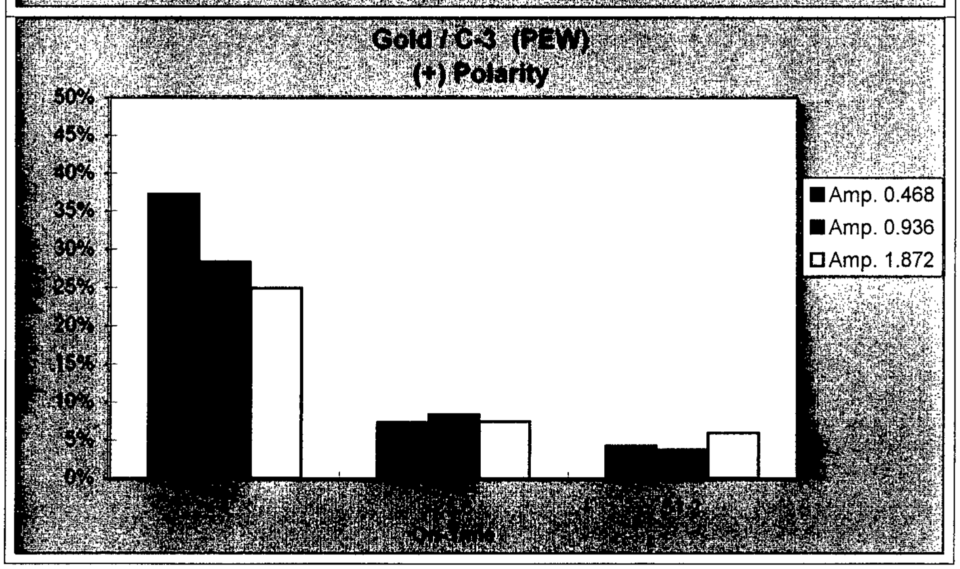
c) PEW



Gold / C-3 (MRR)
(+) Polarity
MRR
250.00
225.00
200.00
175.00
150.00
125.00
100.00
75.00
50.00
25.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



Gold / C-3 (Ra)
(+) Polarity
Ra Average
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



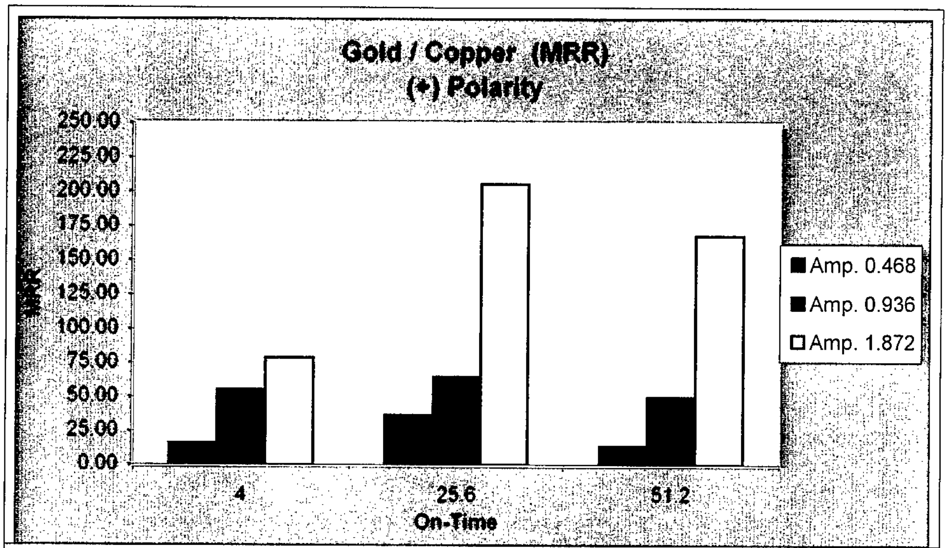
Gold / C-3 (PEW)
(+) Polarity
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

Figure 20: Gold / Copper (+) polarity

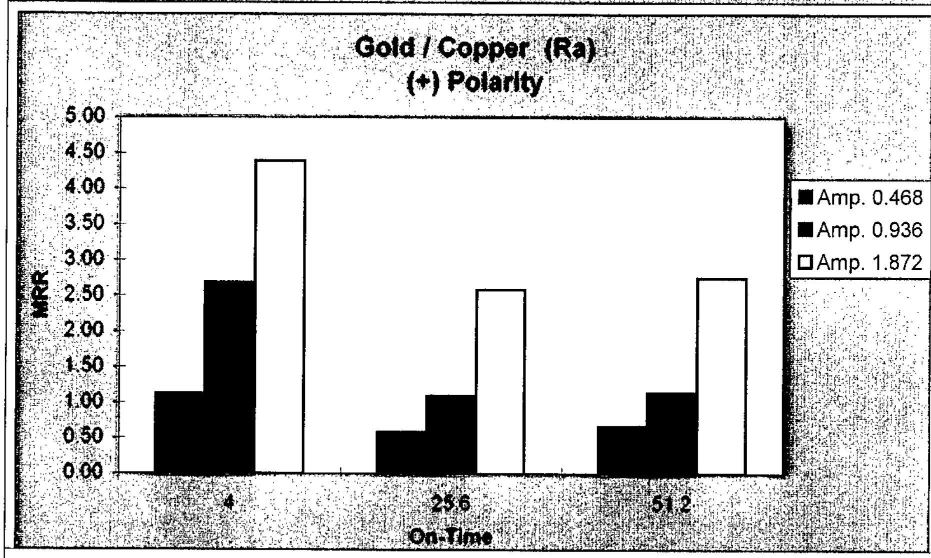
a) MRR

b) Surface Finish (R_a)

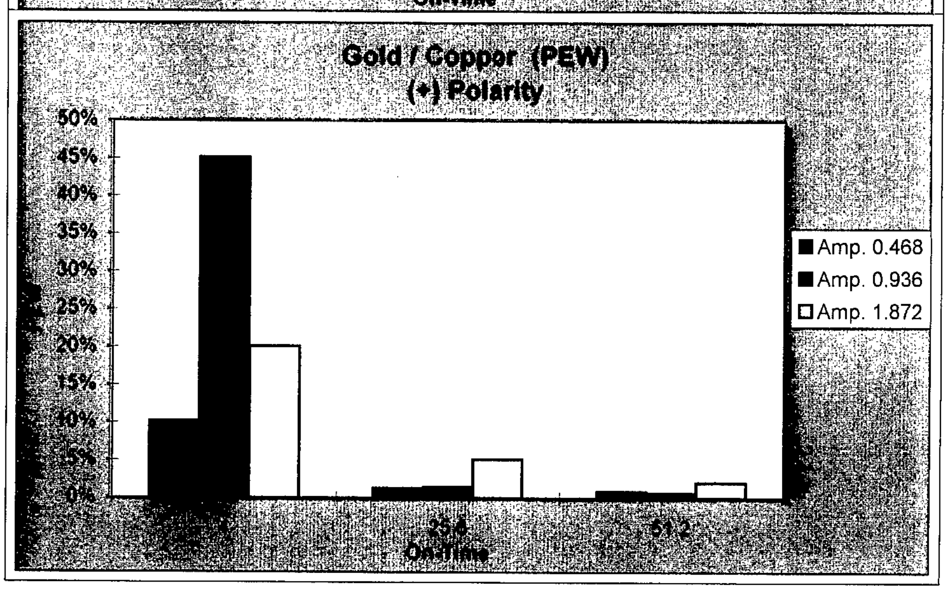
c) PEW



Gold / Copper (MRR)
(+) Polarity
MRR
250.00
225.00
200.00
175.00
150.00
125.00
100.00
75.00
50.00
25.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



Gold / Copper (Ra)
(+) Polarity
MRR
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



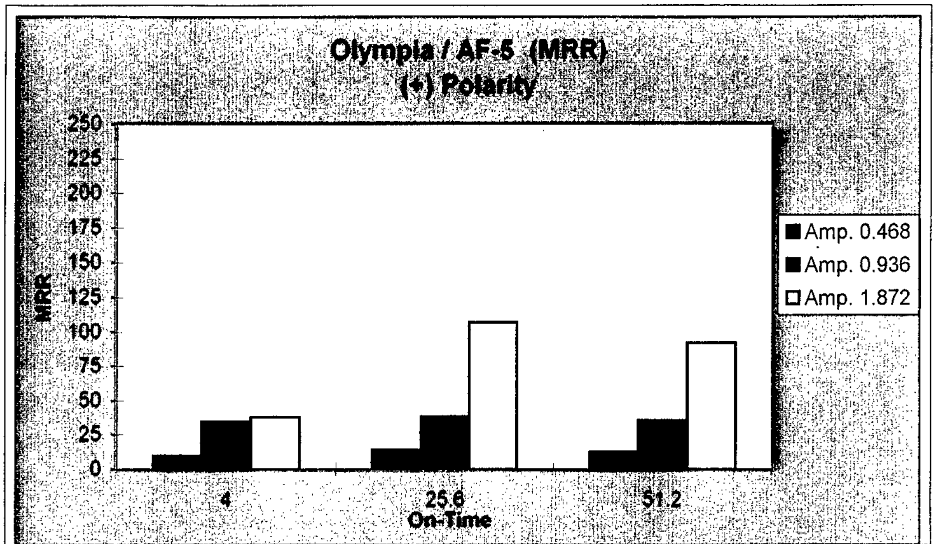
Gold / Copper (PEW)
(+) Polarity
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

Figure 21: Olympia / AF-5 (+) polarity

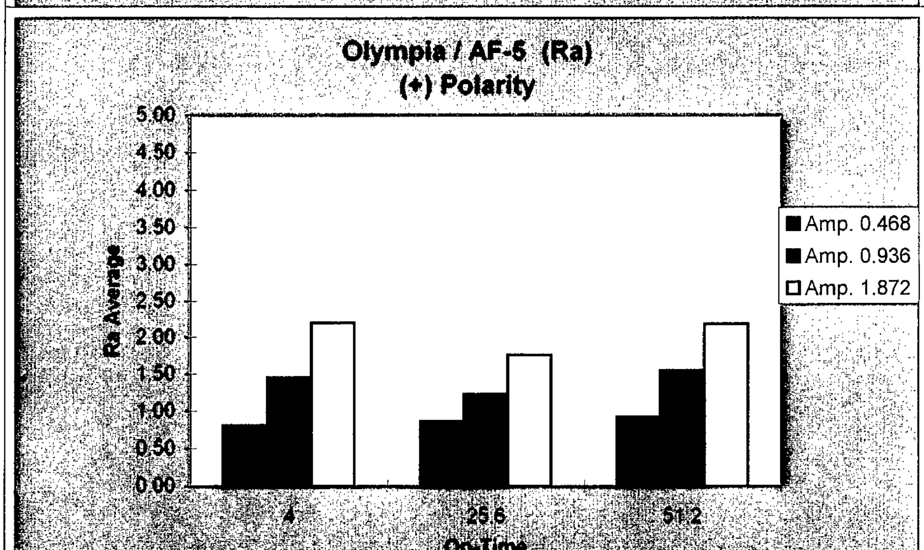
a) MRR

b) Surface Finish (R_a)

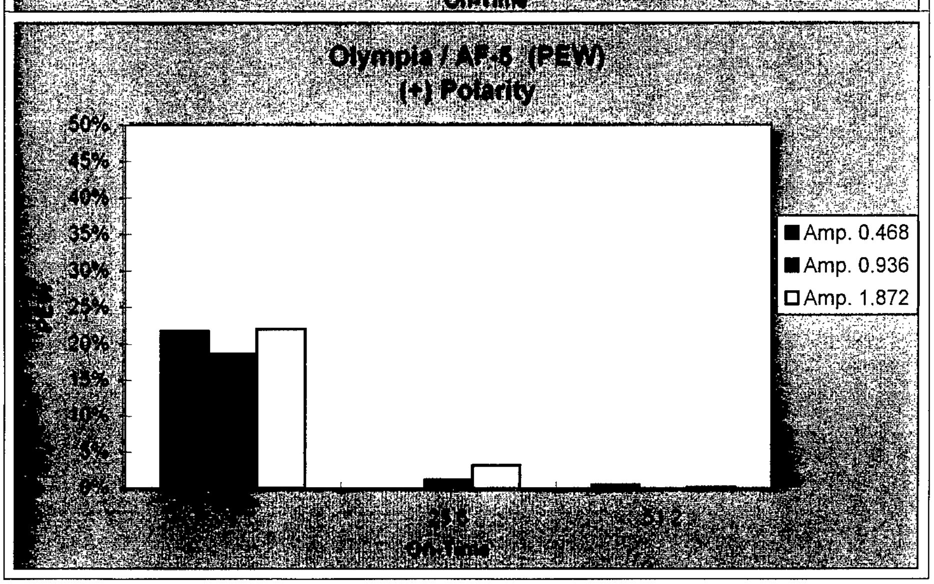
c) PEW



Olympia / AF-5 (MRR)
(+) Polarity
MRR
250
225
200
175
150
125
100
75
50
25
0
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



Olympia / AF-5 (Ra)
(+) Polarity
Ra Average
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



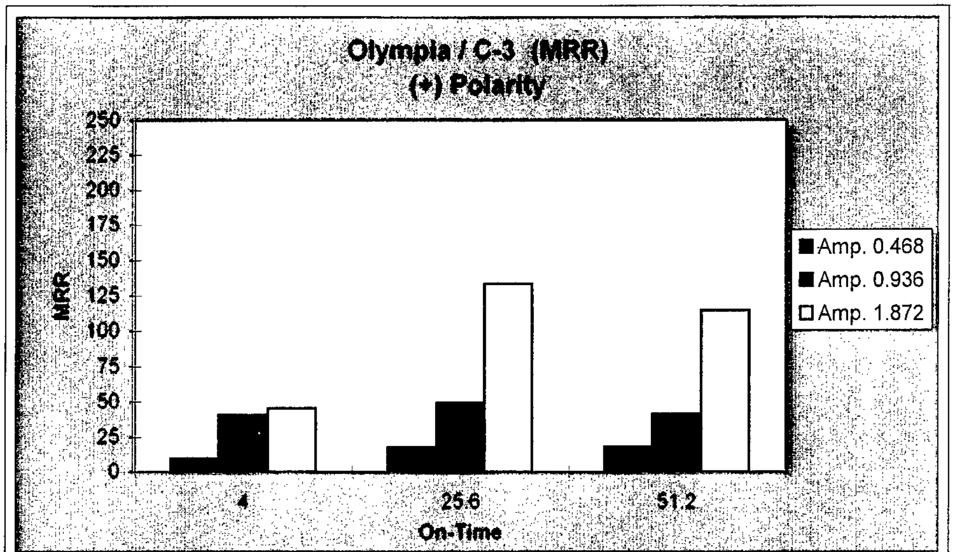
Olympia / AF-5 (PEW)
(+) Polarity
PEW
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

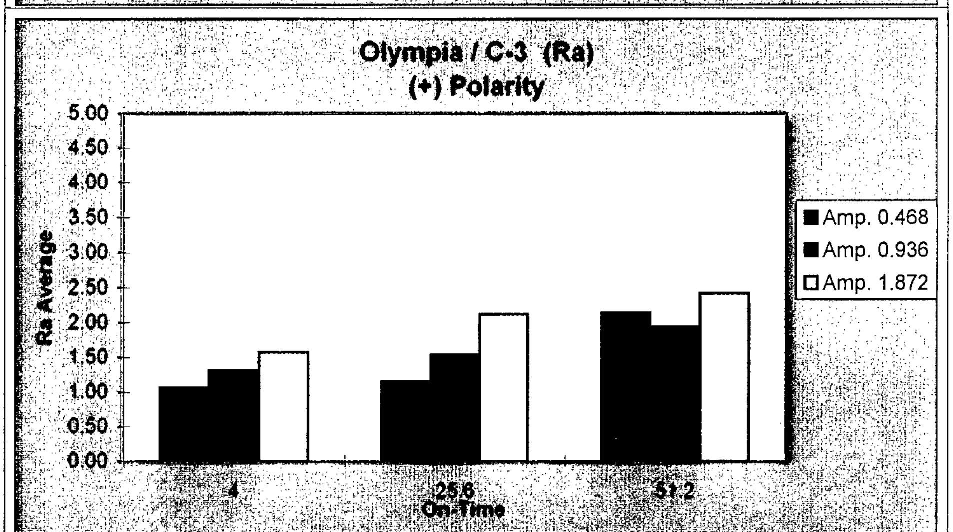
Figure 22: Olympia / C-3 (+) polarity

a) MRR

b) Surface Finish (R_a)

c) PEW


Olympia / C-3 (MRR)
(+) Polarity
MRR
250
225
200
175
150
125
100
75
50
25
0
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872


Olympia / C-3 (Ra)
(+) Polarity
Ra Average
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

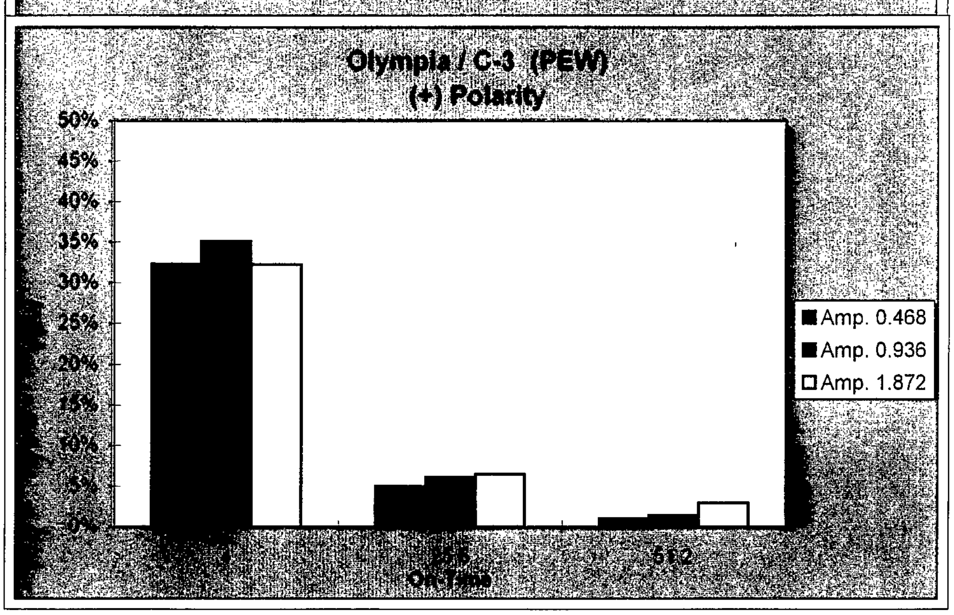
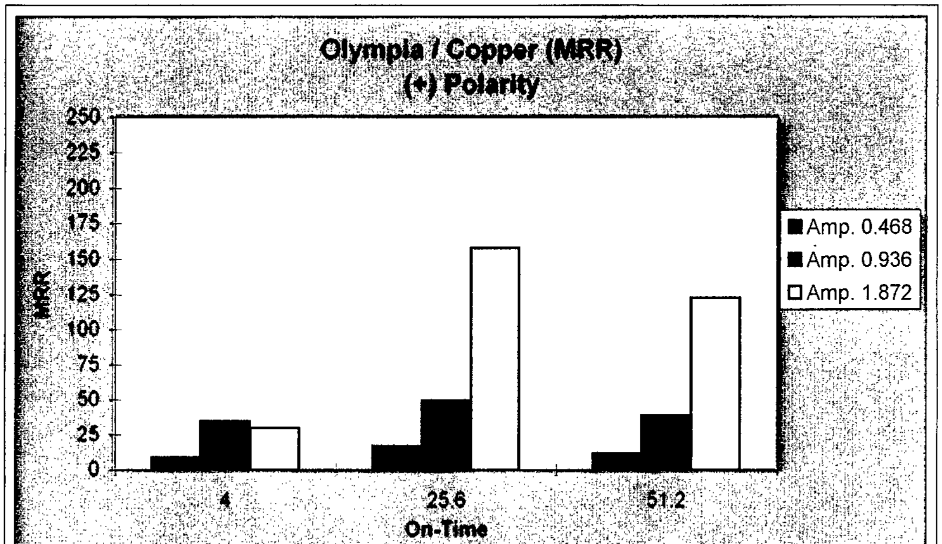

Olympia / C-3 (PEW)
(+) Polarity
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

Figure 23: Olympia / Copper (+) polarity

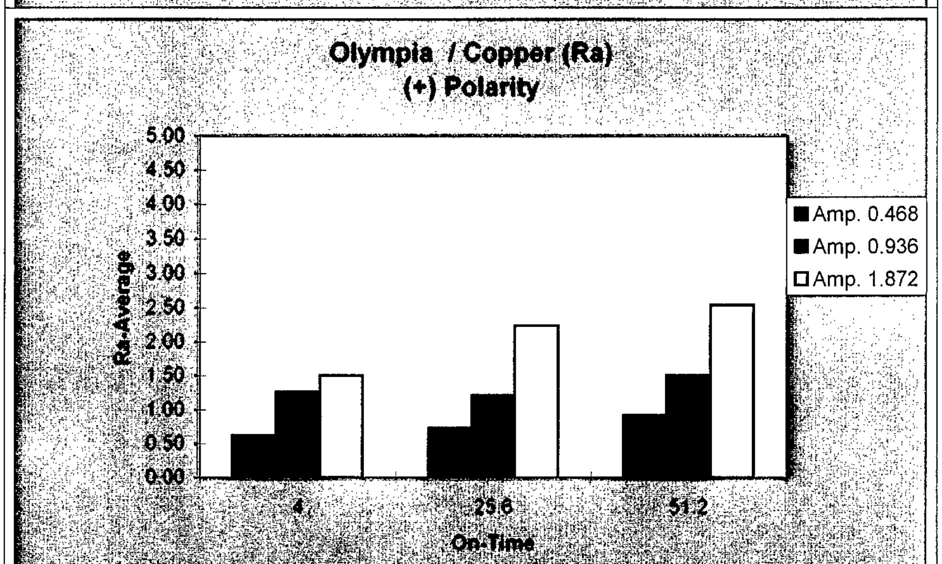
a) MRR

b) Surface Finish (R_a)

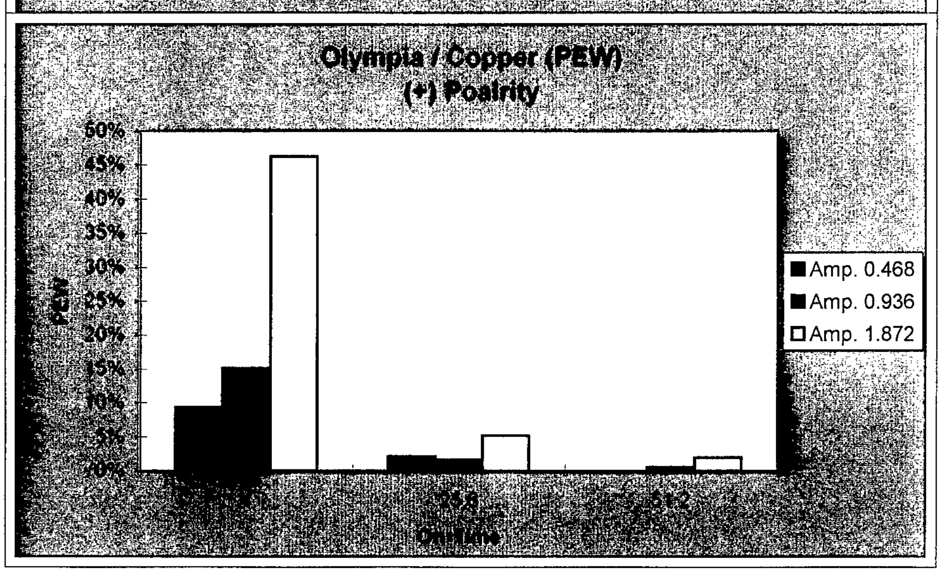
c) PEW



Olympia / Copper (MRR)
(+) Polarity
MRR
250
225
200
175
150
125
100
75
50
25
0
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



Olympia / Copper (Ra)
(+) Polarity
Ra-Average
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



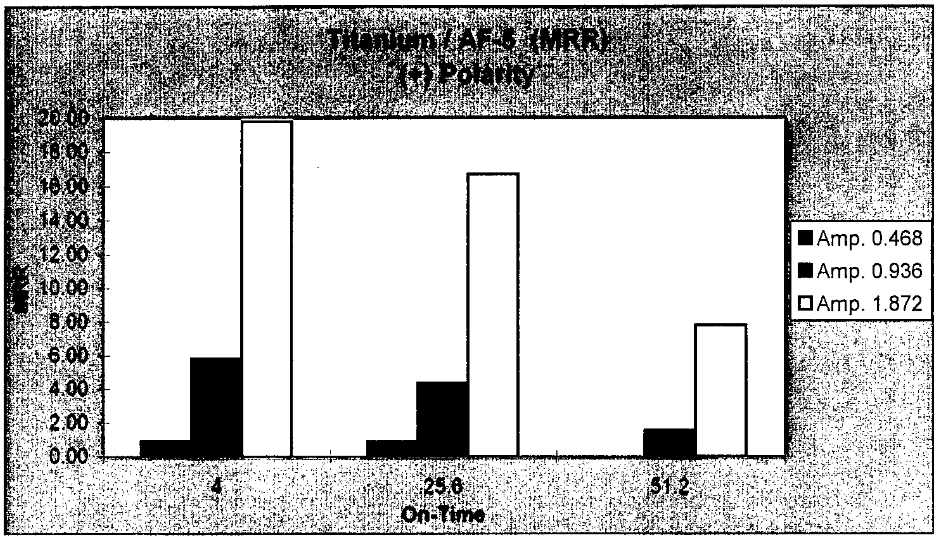
Olympia / Copper (PEW)
(+) Polairity
PEW
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

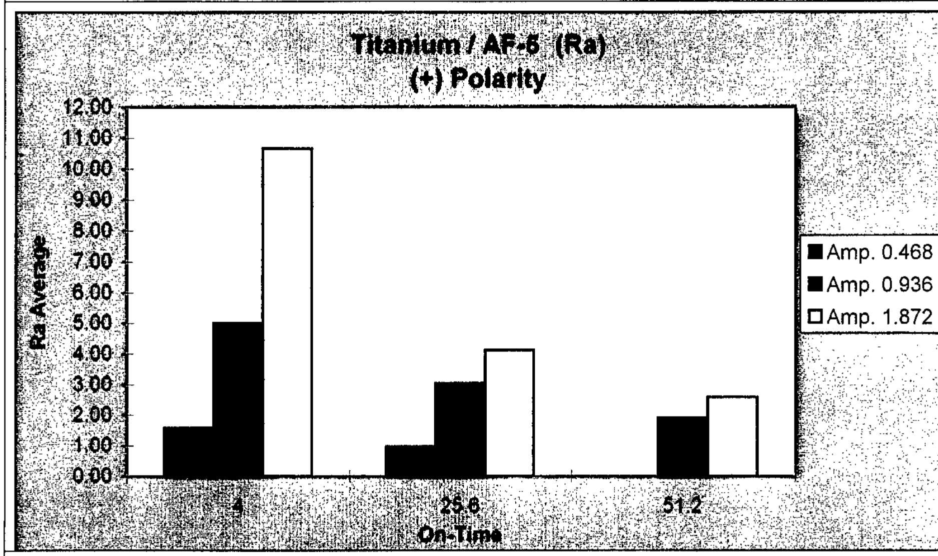
Figure 24: Titanium / AF-5 (+) polarity

a) MRR

b) Surface Finish (R_a)

c) PEW


Titanium / AF-5 (MRR)
(+) Polarity
MRR
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872


Titanium / AF-5 (Ra)
(+) Polarity
Ra Average
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

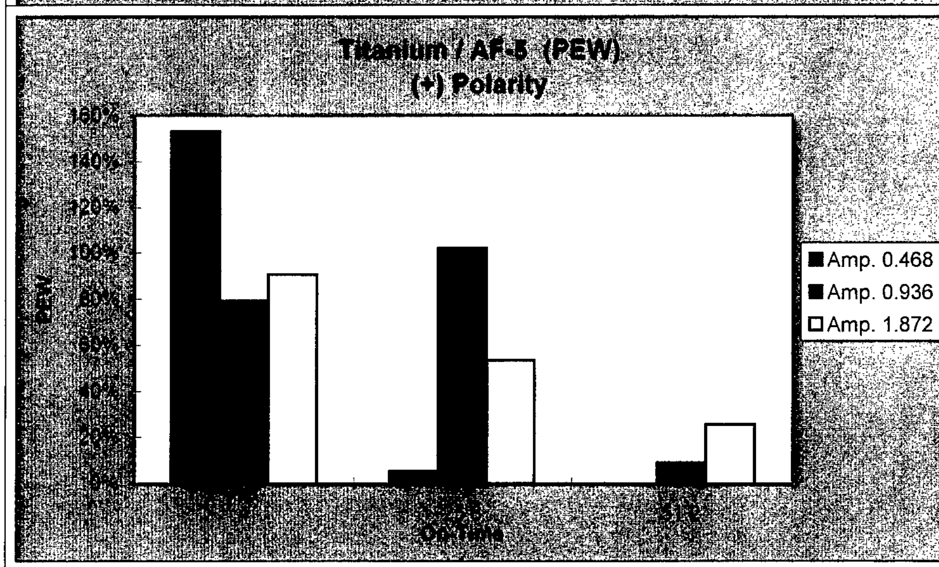
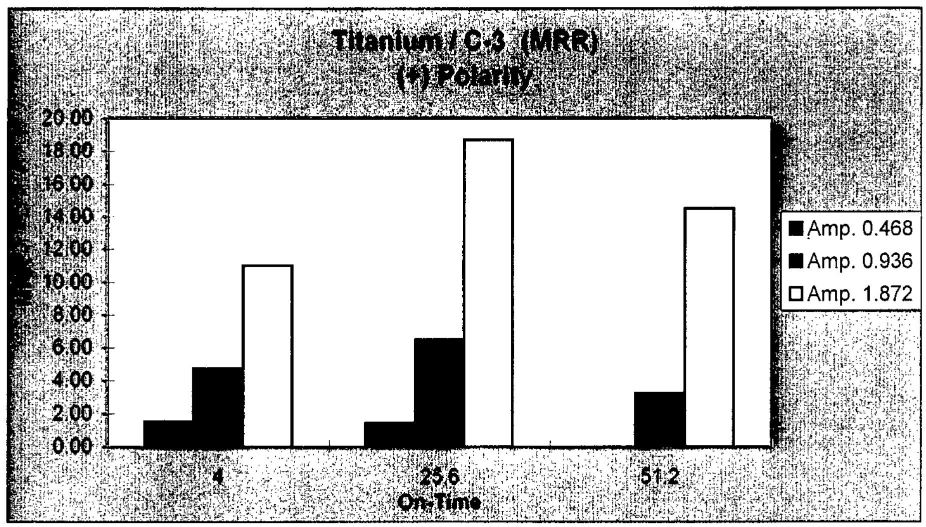

Titanium / AF-5 (PEW)
(+) Polarity
PEW
160%
140%
120%
100%
80%
60%
40%
20%
0%
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

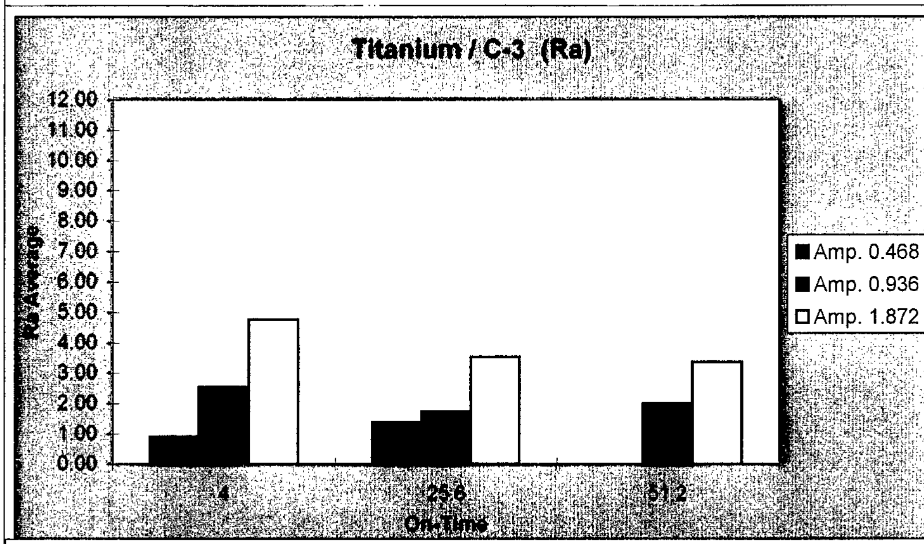
Figure 25: Titanium / C-3 (+) polarity

a) MRR

b) Surface Finish (R_a)

c) PEW


Titanium / C-3 (MRR)
(+) Polarity
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872


Titanium / C-3 (Ra)
Ra Average
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

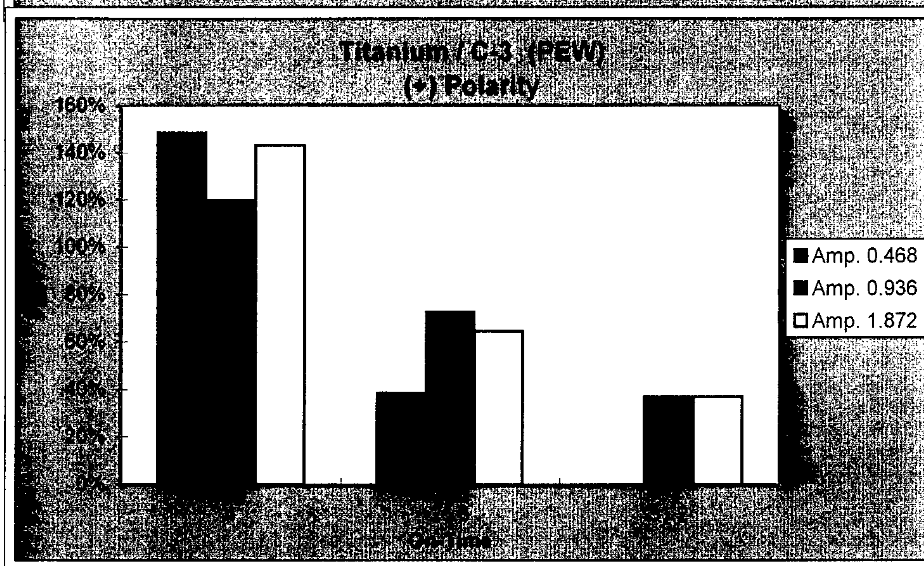
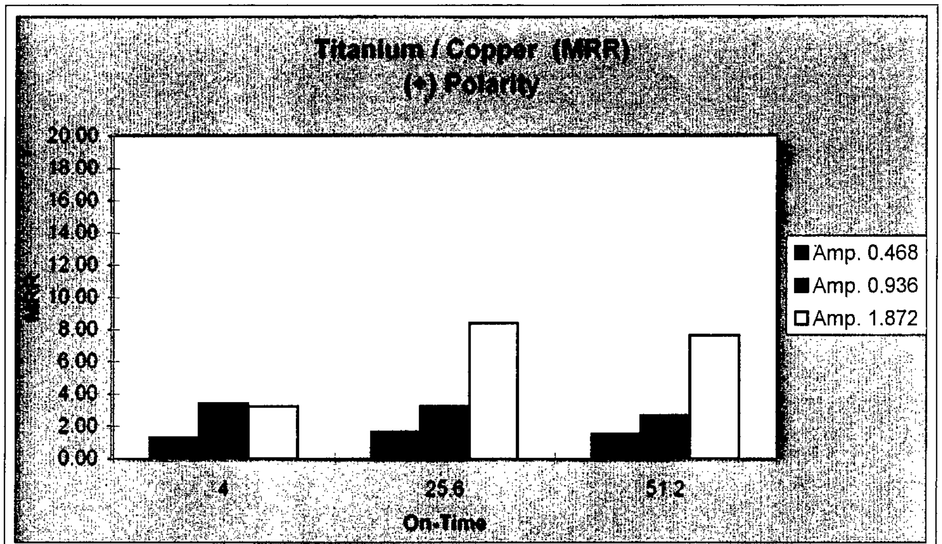

Titanium / C-3 (PEW)
(+) Polarity
160%
140%
120%
100%
80%
60%
40%
20%
0%
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

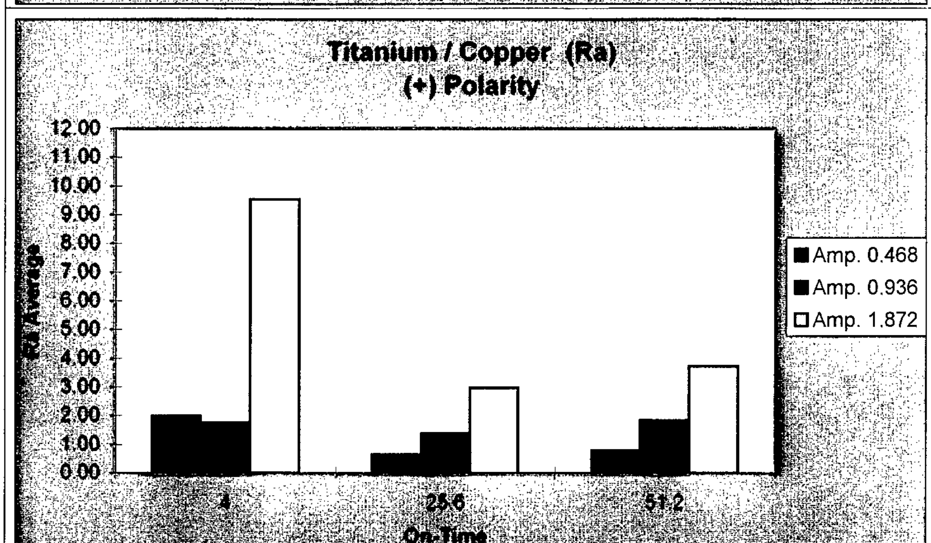
Figure 26: Titanium / Copper (+) polarity

a) MRR

b) Surface Finish (R_a)

c) PEW


Titanium / Copper (MRR)
(+) Polarity
MRR
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872


Titanium / Copper (Ra)
(+) Polarity
Ra Average
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4
25.6
51.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

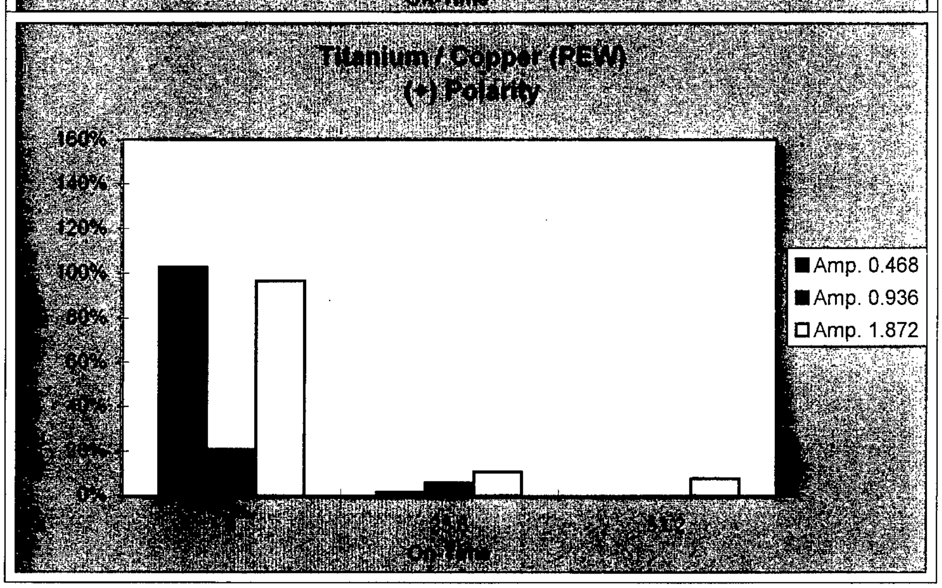
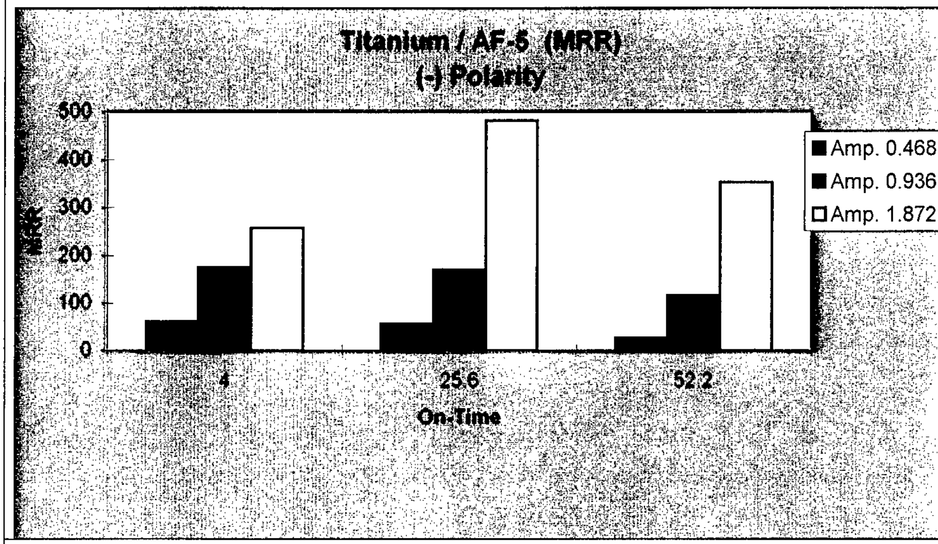

Titanium / Copper (PEW)
(+) Polarity
160%
140%
120%
100%
0%
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

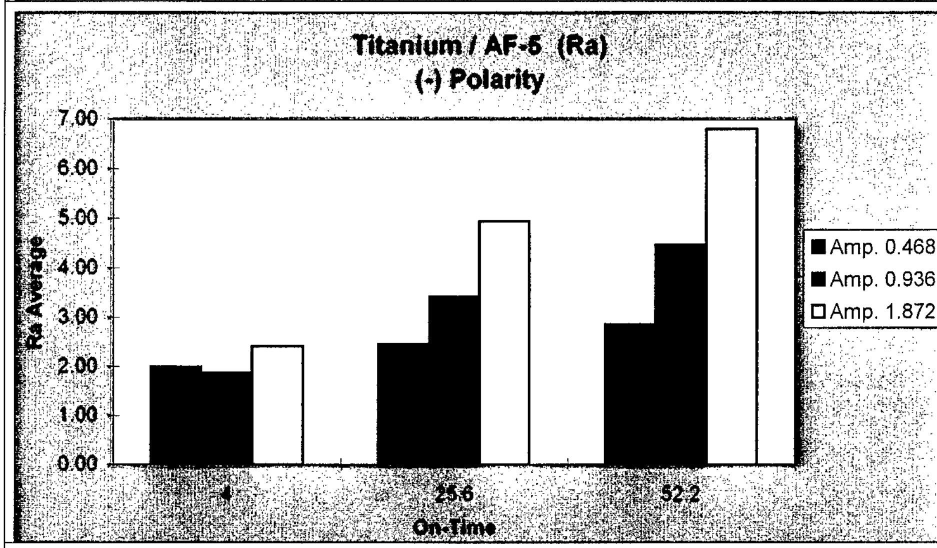
Figure 27: Titanium / AF-5 (-) polarity

a) MRR

b) Surface Finish (R_a)

c) PEW


Titanium / AF-5 (MRR)
(-) Polarity
MRR
500
400
300
200
100
0
4
25.6
52.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872


Titanium / AF-5 (Ra)
(-) Polarity
Ra Average
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4
25.6
52.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

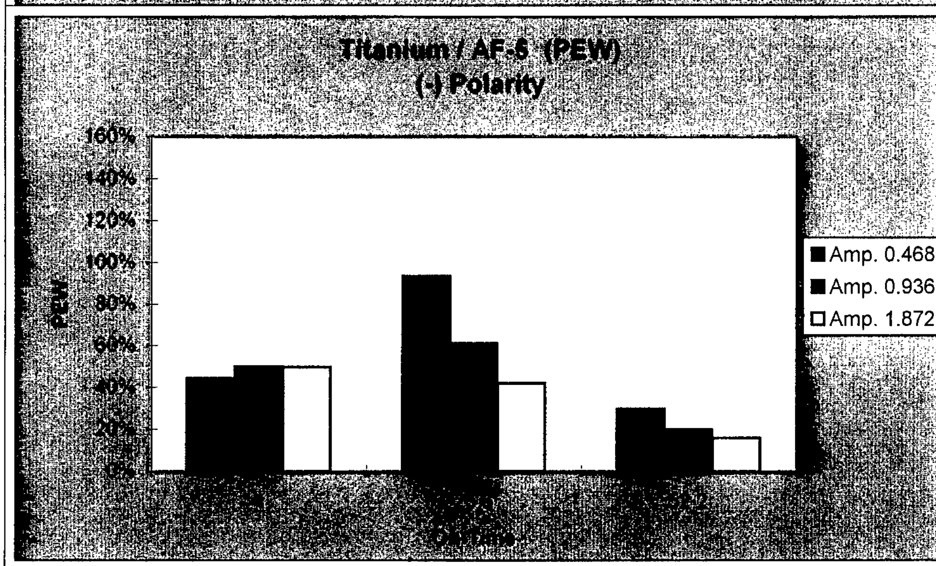
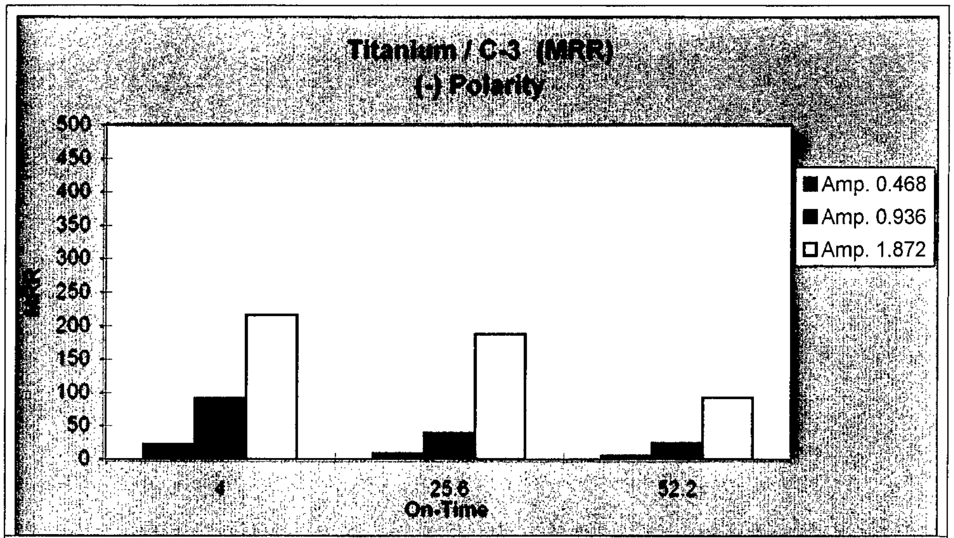

Titanium / AF-5 (PEW)
(-) Polarity
PEW
160%
140%
120%
100%
80%
60%
40%
20%
0%
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

Figure 28: Titanium / C-3 (-) polarity

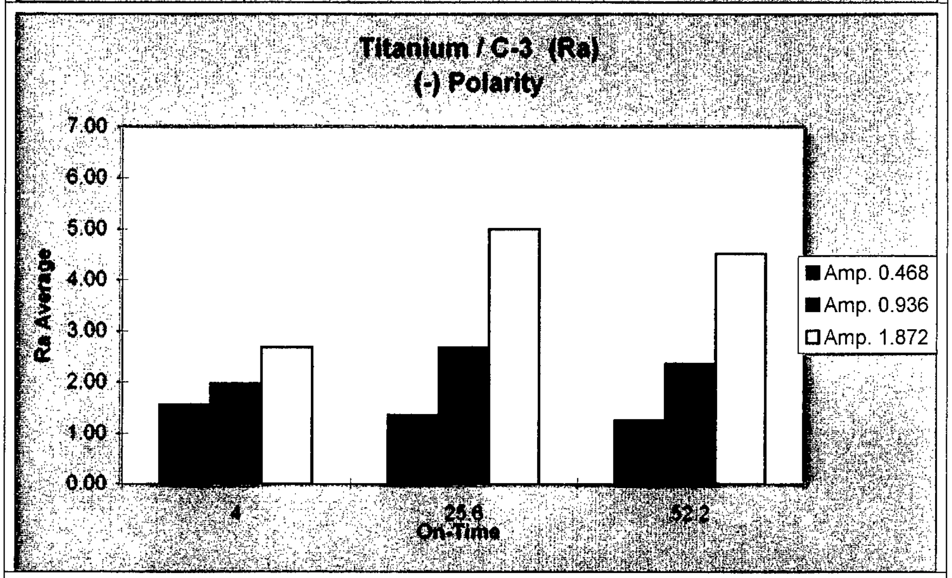
a) MRR

b) Surface Finish (R_a)

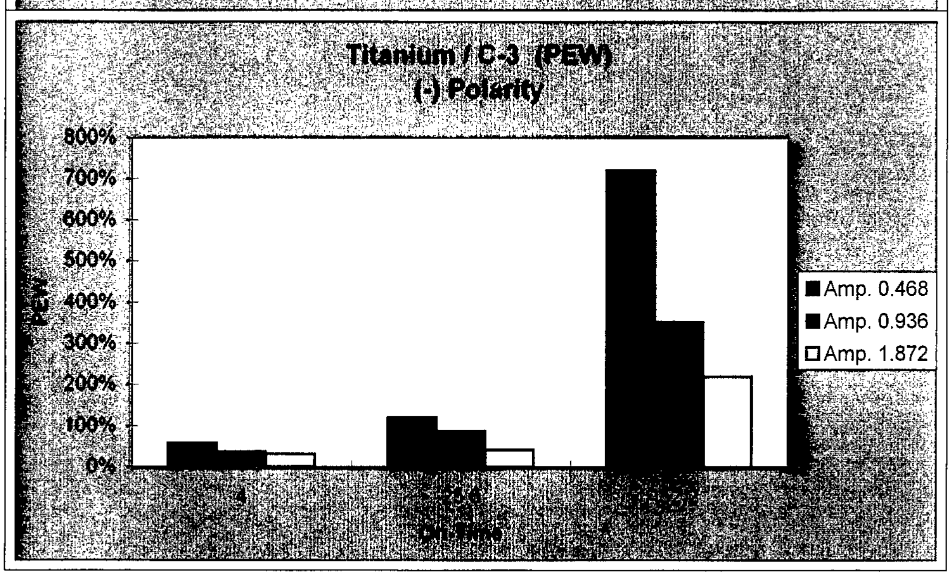
c) PEW



Titanium / C-3 (MRR)
(-) Polarity
MRR
500
450
400
350
300
250
200
150
100
50
0
4
25.6
52.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



Titanium / C-3 (Ra)
(-) Polarity
Ra Average
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4
25.6
52.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872



Titanium / C-3 (PEW)
(-) Polarity
PEW
800%
700%
600%
500%
400%
300%
200%
100%
0%
4
25.6
52.2
On-Time
Amp. 0.468
Amp. 0.936
Amp. 1.872

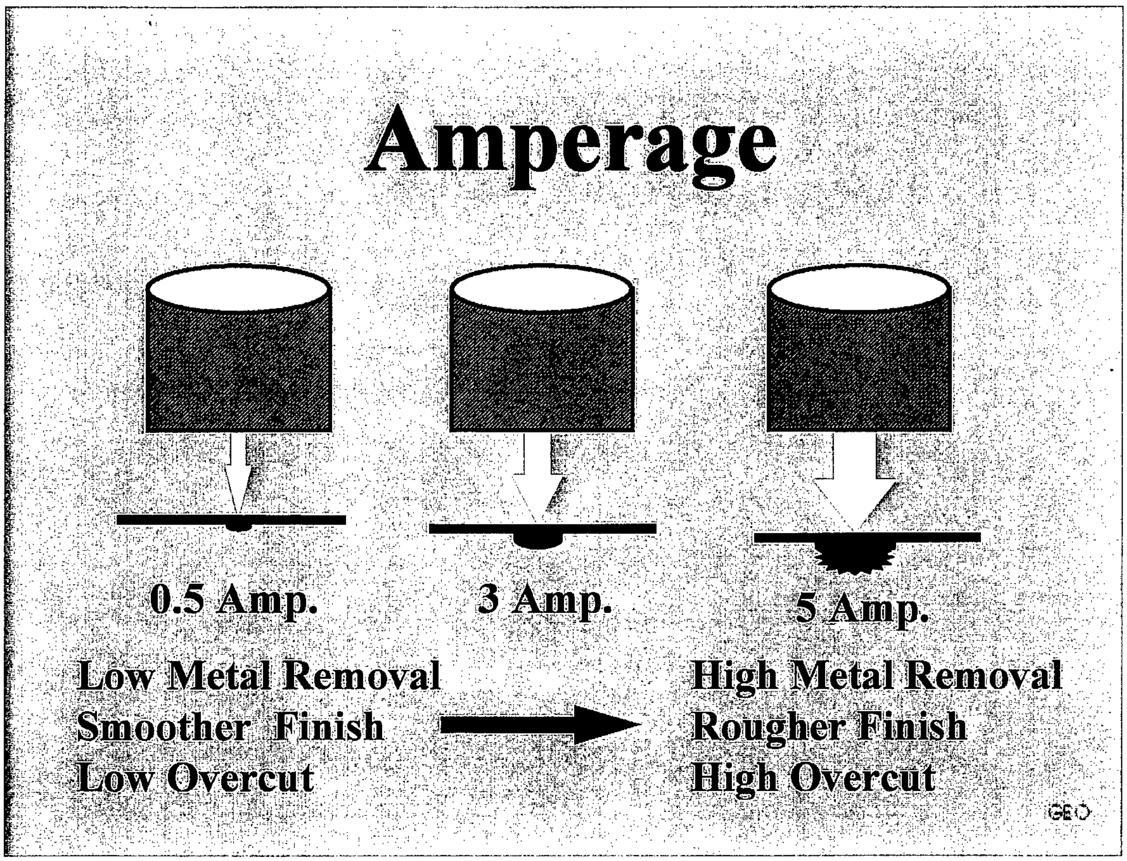
VI. DISCUSSION

The most notable advantage of EDM is that mechanical forces have no influence on the process. Hard, tough, fragile, heat treated, exotic and /or heat sensitive metals that are difficult to machine by conventional techniques can be precisely and easily machined to close tolerances. The only requirements is that the metal (workpiece) be an electrical conductor. The cutting electrode never touch the workpiece so even fragile materials can be machined without distortion. This technique does not produced a chip as metal is removed. The removed particles are disposed of completely by vaporization or reduced to microscopic particles that are flush away from the machining gap by a dielectric fluid. Perhaps some of the greatest advantages of EDM in dentistry are in the machining of implant components and precision attachments as well as correcting casting inaccuracies of implant retained restorations to provide a passive fit.

In conventional machining processes the rate of metal removal, surface finish, accuracy and efficiency are controlled by the motor horsepower, revolution per minute of the cutting instrument, and feed rates. Controlling the discharge of electrical energy is the key of the EDM machining process. As shown previously (page 60),varying the on-time and/or off-time will change the duty cycle and the frequency. These changes plus varying the peak current or amperage will affect the MRR, surface finish and electrode wear.

The size of the crater produced in the workpiece by the discharge is determined by the size or the energy of the discharge. The energy of the discharge is determined by the gap voltage during the discharge, the discharge current (amperage) and length of time (on-time) that the current flows. MRR, surface finish and electrode wear are directly affected by amperage and on-time changes. For surface finishes the amount of current (amperage) is more influential than the length of time (on-time). In this investigation highest amperage produced highest MRR regardless of metal electrode combination (Figure 29). However the highest machining amperage used in this study (1.872 A) exceeded the maximum amperage recommended (Fig. 9). The maximum recommended peak current in relation to electrode frontal area was (1.76 A) which multiply by the 60% duty cycle used in this investigation produced a maximum machining amperage of 1.05 A. This excessive amperage created distortion, deformation and damage of the electrodes and workpieces. This is of extreme importance in dental applications in which maximum precision and accuracy is imperative. For dental application the EDM operator most have knowledge of all the machining parameters, specially the maximum amperage recommended related to the total frontal area of the electrode. Another factor to consider when selecting the machining amperage is the irregularities of the surfaces to be machined. If the electrode has different planes and surfaces maximum amperage will depend on the electrode area that is in close proximity or contact with the workpiece. When using the EDM process to correct casting discrepancies and/or achieve a passive fit of implant restoration the initial electrode/workpiece contact is minimal, if the maximum calculated amperage according to the total surface area is used, damage to the workpiece and the electrode may occur affecting the accuracy and precision of the final product.

Figure 29: Relationship of amperage to MRR, surface finish and overcut


Amperage
0.5 Amp.
3 Amp.
5 Amp.
Low Metal Removal
Smoother Finish
Low Overcut
High Metal Removal
Rougher Finish
High Overcut

For this kind of procedure minimal amperage is recommended. Sparks will be observed only in a minimal electrode/workpiece area of the machining surfaces. As the discrepancies are corrected, more spark areas will be observed and amperage may be raised in minimal increments but without reaching the maximum recommended. However consideration on the surface finish may be an indication of keeping the amperage to a minimum. Also the use of high amperage will increase the overcut (Figure 10).

Polarity refers to an electrical condition determining the direction of the current flow relative to the electrode. Positive polarity provide better wear resistance of the electrode, better finishes but lowest MRR. Titanium produced very low MRR when positive polarity is used. The metallurgical industry recommends the use negative polarity for faster cuts (roughing) and higher MRR, then changing to positive polarity to improve the surface finish (Poco 1993). Due to the high conductivity, low resistivity and low melting point of copper no machining was possible between titanium and copper using negative polarity.

This investigation demonstrate that high or long on-time settings do not produced the highest MRR. Long on-times can put the electrode in a no-wear situation. However long on-times may be counter productive, creating MRR reduction. If the on-time is too long and the off-time too short, the ejected workpiece material will not be flushed away by the flow of the dielectric fluid and will be redeposited in the workpiece cavity reducing the MRR. On-times of 25.5 μSec provided the best MRR for gold, Olympia and titanium (+) polarity when all other variables remained constant.

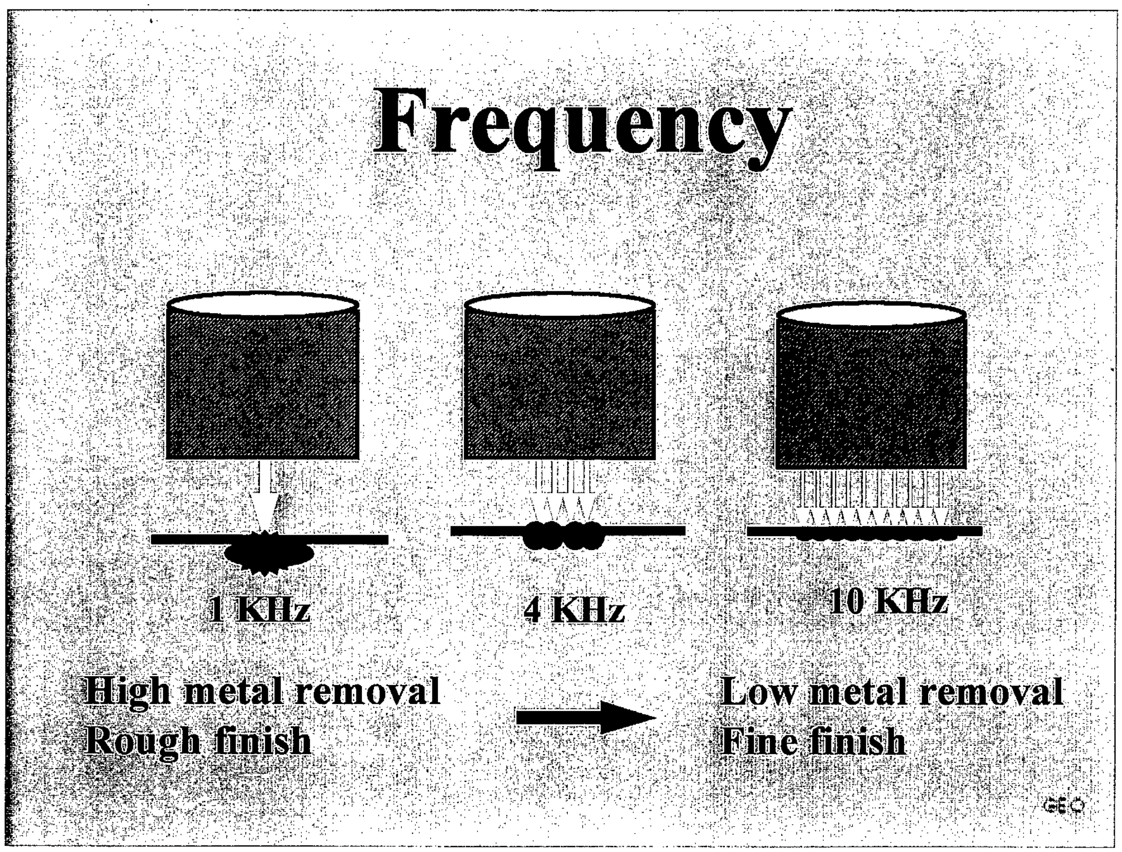
On-time variations have more effect on the electrode wear than amperage variation. When machining in positive polarity, minimum wear of the electrode was observed when using on-times of 25.6 and 51.2 μSec. Marked increased of electrode wear and surface finish improvement were observed when lowering the on-time to 4.0 μSec.

Duty cycle is a percentage of the on-time relative to the total cycle time (on-time + off-time). Duty cycle % is also expressed by the incorrect term "on-time%". Generally the higher the Duty cycle %, the higher the MRR and the rougher the finished surfaces. In this investigation the duty cycle was maintained constant to 60%.

Frequency, the number of cycles produced across the gap in one second, also affects the surface finish.. The higher the frequency the finer the surface finish (Figure 30). As the number of cycles per second increases the length of the on-times decreases, for a constant duty cycle. Short on-times removed very little metal and create very little craters producing smoother finishes with less thermal damage.

The ability of an electrode to produce and maintain detail is directly related to its resistance to wear and its machinability. If an electrode can successfully resist erosion at its most vulnerable points (corners), then overall wear is minimized and maximum electrode life achieved. There are four different types of wear; end, corner, side, and volumetric. In this investigation only the end wear was considered. End wear is the reduction in the length of the electrode during the EDM process. The amount is calculated by measuring the length of the electrode before and after the cut, and subtracting the length after the cut original length. However corner wear is usually the

Figure 30: Relationship of frequency to MRR and surface finish.


Frequency
1 KHz
4 KHz
10 KHz
High metal removal
Rough finish
Low metal removal
Fine finish

most important, since it determines the degree of accuracy of the final cut. Electromagnetic fields tend to concentrate at the electrode corners subjecting the corners to greater wear. the sharper the angle, the more sparks are generated in this area and the more heat buildup, causing accelerated wear in the corner areas of the electrode. Corner wear can be determined by measuring the electrode on an optical comparator. The apparent corner wear is the length lost at the 90^0 angle. True corner wear is then calculated by subtracting the amount of end wear to the apparent corner wear. Side wear refers to the wear along the side walls of the electrodes, and volumetric wear refers to the combined wear over the entire cutting surface of the electrode versus the amount of metal removed. Volumetric wear is usually calculated from the weight changes. When fine details or sharp angles are involved in an EDM machining application more than one electrode most be used. A new electrode with a low amperage setting should be consider before completing the machining process. These will produce a more accurate reproduction of details, better accuracy and a better finish.

Some combination of machining parameter produced minimal or no wear of the electrode. In the EDM process no-wear is considered to be 1.00% or less electrode wear is achieved in a machining operation. The parameters necessary for a no-wear condition are positive polarity and long on-times. The off-time is set as short as possible to maintain stable machining conditions. During the no wear situation the electrode will take on a silvery coating that is the effect of the workmetal plating the electrode. However, too long on-times will cause too much plating action causing nodules on the end of the electrode, distorting its shape. No wear settings do not produce the fastest MRR and smoothest finishes, In this investigation no-wear was obtained in various metal-electrode combination with on-times of 51.2 μSec.

The dielectric fluid Is an important variable in the EDM process. It has three main functions: a) it is an insulator between the tool and work, b) it is a coolant, and c) it is a flushing medium. The desirable characteristics of dielectric fluid are high dielectric strength, low viscosity, high flash point and low toxicity. Hydrocarbons oils are most commonly used for conventional EDM.

Ideal flushing pressure is 3-5 psi. Elevated flushing pressures can created excessive wear of the electrodes. Through the electrode flushing will allow better flow of dielectric fluid on the gap area. However when through the electrode flushing is not possible in a machining application the following recommendations must be considered: external flushing, increase the gap space and increase the off-time The last two recommendations will allow the dielectric fluid to penetrate and better clean the machining gap. One of the advantages when machining implant components is that the center screw access hole allow the particles to escape and the dielectric fluid to circulate better in the gap area, improving not only the flushing conditions, but also eliminating the possibility of gas pocket formation in the electrode cavity. For better performance of the dielectric fluid a filter with less than 5 micron particle size must be used to eliminate undesirable particle than can create unstable machining and arcing. A low viscosity and clean dielectric fluid will improve the surface finish and the efficiency of the machining process.

Electrode material selection is very important and must be considered according to the specific application and metal-electrode combination. The most important performance factors to consider are MRR, wear resistance, surface finish, machinability and material cost. In this investigation copper provide adequate MRR and superior finishes compare with the other two electrode materials. Orraca *et al.*, 1996 reported surface finishes of 0.2 R_a when using copper electrodes, currents of 0.078 A and on-times of 0.5 μSec. with gold, Olympia and titanium as workpieces. However one of the limitations with copper is its poor machinability, which limit its applications to implant cases or cases in where standardized electrodes can be produced. AF-5 and C-3 are very easy to machine providing versatility in the size and shape of the EDM electrode to be fabricated. Rapid prototyping systems, CAD/CAM and CNC milling machines can be use for future fabrication of EDM electrodes. This method will allow the fabrication of multiple identical electrodes which eliminates error due to electrode wear

The main disadvantages of initial commercially available EDM machines were the cost, size and weight of this machines. The average cost of the machines was approximately $20,000, making them too expensive for many dental laboratories. These machines were about five feet long three feet wide and six feet tall with a weight between 1000 to 1500 pounds, creating also a space problem. New EDM machines are now available (since 1996) for small machining applications and dental laboratory use, these machines cost approximately $5,000, weigh about 100 pounds and are convenient in size, making then not only affordable but easy to place in any laboratory without major space modification.

VII. CONCLUSION

EDM electrode compositions, currents (amperages) and on-times were evaluated for their effects on MRR, surface finish (R_a) and electrode wear in representative dental alloys,. Suitable starting values were identified which yield acceptable combinations of those parameters for each electrode-metal combination. This investigation identified initial machining parameters (Amperage and on-time) for representative dental alloys and electrode materials.. Future investigations should include additional EDM variables (e.g., overcut, electrode corner wear, dielectric fluid composition and flushing pressure). In addition, the regions surrounding the best combinations of parameters identified in this study should be investigated to further refine the optimal combinations. EDM shows great promise in prosthodontics not only in refining the fit of castings, fabrication of custom implant and attachment components but fas a useful tool for dental device manufacturing to improve functional and esthetic results.

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Appendix

MEANS VALUES AND STANDARD DEVIATIONS

OF THE CALCULATED:

METAL REMOVAL RATE (MRR)

SURFACE FINISH

PERCENTAGE OF ELECTRODE WEAR (PEW)

AVERAGE CUT

ELECTRODE END WEAR

EDM Data
(Positive Polarity)

Parameter: MRR

Metal:Gold **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	13.132	0.575	11.682	0.680	13.795	0.231	
0.936	40.251	3.426	37.865	9.944	35.850	2.120	
1.872	91.581	6.146	96.420	2.246	108.923	2.632	BC

Metal:Gold **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	14.479	1.332	23.799	2.838	17.858	1.211	A C
0.936	40.623	0.653	67.948	1.112	46.390	2.783	ABC
1.872	107.176	4.288	199.279	4.032	115.525	4.287	ABC

Metal:Gold **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	15.920	0.934	36.649	1.873	13.649	0.314	A C
0.936	55.096	3.306	64.767	1.578	49.779	1.591	ABC
1.872	78.691	5.406	205.846	3.465	168.218	2.879	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: MRR

Metal:Olympia **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	9.810	0.822	14.243	0.379	12.530	0.252	
0.936	34.537	6.846	38.273	1.391	35.454	0.910	
1.872	38.057	6.329	107.030	3.069	92.247	3.076	ABC

Metal:Olympia **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	9.509	1.661	17.452	0.192	18.044	0.321	AB
0.936	41.146	0.772	49.820	0.797	41.951	0.520	A C
1.872	45.961	4.250	133.608	4.016	114.904	2.003	ABC

Metal:Olympia **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	8.685	1.154	16.875	0.268	11.983	0.159	A
0.936	34.753	1.300	49.575	7.629	39.250	0.310	ABC
1.872	29.994	1.418	157.882	4.819	122.866	2.526	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: MRR

Metal:Titanium **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.914	0.108	0.884	0.027	0.000	0.000	BC
0.936	5.811	0.740	4.389	0.349	1.528	0.078	ABC
1.872	19.805	0.017	16.746	0.443	7.808	0.517	ABC

Metal:Titanium **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	1.509	0.234	1.441	0.050	0.000	0.000	BC
0.936	4.731	0.921	6.497	0.106	3.207	0.151	ABC
1.872	11.020	0.636	18.718	0.255	14.506	0.371	ABC

Metal:Titanium **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	1.305	0.631	1.668	0.140	1.550	0.022	
0.936	3.434	0.578	3.255	0.145	2.686	0.181	
1.872	3.241	0.439	8.433	1.279	7.657	0.254	AB

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: PEW(%)

Metal:Gold **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	27.540	1.570	3.468	0.640	1.269	0.021	ABC
0.936	23.227	1.058	5.286	0.278	1.633	0.586	ABC
1.872	27.006	0.265	5.815	0.496	1.821	0.180	ABC

Metal:Gold **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	37.193	3.729	7.420	0.845	4.272	0.766	ABC
0.936	28.358	1.155	8.410	0.525	3.771	0.735	ABC
1.872	24.959	0.778	7.438	0.516	5.963	0.269	AB

Metal:Gold **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	10.146	0.694	1.291	0.623	0.856	0.742	AB
0.936	59.867	4.711	1.440	0.310	0.704	0.022	AB
1.872	10.428	1.158	5.105	0.426	2.081	0.035	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: PEW(%)

Metal: Olympia **Electrode: AF-5**

Average Current	On-Time=4 uSec mean	SD	On-Time=25.6 uSec mean	SD	On-Time=51.2 uSec mean	SD	
0.468	21.790	3.756	0.000	0.000	0.456	0.790	AB
0.936	18.688	2.836	1.213	0.499	0.000	0.000	AB
1.872	22.077	3.702	3.164	0.233	0.131	0.227	AB

Metal: Olympia **Electrode: C-3**

Average Current	On-Time=4 uSec mean	SD	On-Time=25.6 uSec mean	SD	On-Time=51.2 uSec mean	SD	
0.468	32.316	2.875	5.012	0.056	0.970	0.017	ABC
0.936	35.150	0.275	6.082	0.733	1.392	0.489	ABC
1.872	31.834	1.069	6.468	0.329	2.940	0.418	ABC

Metal: Olympia **Electrode: Copper**

Average Current	On-Time=4 uSec mean	SD	On-Time=25.6 uSec mean	SD	On-Time=51.2 uSec mean	SD	
0.468	9.414	0.337	2.075	0.033	0.000	0.000	ABC
0.936	15.120	0.576	1.632	0.145	0.593	0.514	ABC
1.872	46.279	0.263	5.165	0.584	1.994	0.041	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: PEW(%)

Metal: Titanium **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	152.794	16.059	5.316	4.609	.	.	A
0.936	79.354	5.827	102.251	4.693	9.162	0.475	ABC
1.872	90.835	0.787	53.607	3.843	25.730	0.967	ABC

Metal: Titanium **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	148.532	32.431	38.531	3.881			A
0.936	119.788	18.722	72.576	2.795	36.966	3.916	ABC
1.872	143.213	8.157	64.571	0.761	36.873	2.632	ABC

Metal: Titanium **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	102.610	41.997	1.475	2.555	0.000	0.000	AB
0.936	20.871	5.612	5.769	1.440	0.000	0.000	
1.872	96.619	9.691	10.813	0.786	7.629	1.147	AB

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: Surface Finish

Metal: Gold **Electrode: AF-5**

Average Current	On-Time=4 uSec mean	SD	On-Time=25.6 uSec mean	SD	On-Time=51.2 uSec mean	SD	
0.468	0.823	0.137	1.053	0.400	0.720	0.017	
0.936	1.213	0.140	1.200	0.100	1.357	0.140	
1.872	2.557	0.320	1.700	0.170	1.957	0.098	AB

Metal: Gold **Electrode: C-3**

Average Current	On-Time=4 uSec mean	SD	On-Time=25.6 uSec mean	SD	On-Time=51.2 uSec mean	SD	
0.468	0.820	0.085	0.870	0.100	1.043	0.103	
0.936	1.320	0.017	1.233	0.035	1.413	0.051	
1.872	1.400	0.170	2.010	0.085	2.313	0.298	ABC

Metal: Gold **Electrode: Copper**

Average Current	On-Time=4 uSec mean	SD	On-Time=25.6 uSec mean	SD	On-Time=51.2 uSec mean	SD	
0.468	1.123	0.764	0.590	0.035	0.667	0.035	
0.936	2.690	0.131	1.100	0.118	1.147	0.068	AB
1.872	4.387	0.945	2.590	0.443	2.753	0.137	AB

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: Surface Finish

Metal: Olympia **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec	
Current	mean	SD	mean	SD	mean	SD
0.468	0.810	0.085	0.867	0.058	0.923	0.050
0.936	1.457	0.191	1.233	0.035	1.553	0.068
1.872	2.200	0.979	1.767	0.035	2.187	0.051

Metal: Olympia **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	1.067	0.035	1.157	0.121	2.143	0.051	BC
0.936	1.313	0.223	1.547	0.040	1.947	0.133	ABC
1.872	1.577	0.050	2.120	0.017	2.423	0.136	ABC

Metal: Olympia **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.623	0.040	0.733	0.035	0.923	0.068	BC
0.936	1.267	0.180	1.223	0.040	1.510	0.101	BC
1.872	1.513	0.191	2.247	0.068	2.543	0.051	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: Surface Finish

Metal: Titanium **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	1.587	1.342	0.967	0.131	0.000	0.000	
0.936	5.010	3.175	3.053	0.754	1.913	0.140	B
1.872	10.653	0.266	4.133	0.065	2.587	0.125	B

Metal: Titanium **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.910	0.085	1.380	0.079	0.000	0.000	
0.936	2.553	1.639	1.737	0.190	2.000	0.030	C
1.872	4.767	0.265	3.543	0.221	3.367	0.503	AB

Metal: Titanium **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	1.990	1.888	0.647	0.040	0.780	0.017	
0.936	1.753	1.020	1.390	0.017	1.843	0.163	
1.872	9.533	1.890	2.977	0.050	3.733	0.174	AB

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: Average Cut(mm/hr)

Metal: Gold **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.750	0.033	0.668	0.039	0.788	0.013	
0.936	2.301	0.196	2.164	0.568	2.049	0.121	
1.872	5.234	0.352	5.511	0.128	6.225	0.151	BC

etal: Gold **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.828	0.076	1.360	0.162	1.021	0.069	A C
0.936	2.322	0.038	3.883	0.064	2.651	0.159	ABC
1.872	6.125	0.245	11.389	0.230	6.601	0.245	ABC

etal: Gold **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.910	0.053	2.095	0.107	0.780	0.018	A C
0.936	3.149	0.189	3.702	0.090	2.845	0.091	ABC
1.872	4.497	0.309	11.764	0.198	9.613	0.164	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: Average Cut(mm/hr)

Metal: Olympia **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.561	0.047	0.814	0.022	0.716	0.015	
0.936	1.974	0.391	2.187	0.079	2.026	0.052	
1.872	2.175	0.362	6.117	0.176	5.272	0.176	ABC

Metal: Olympia **Electrode: C-3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.543	0.095	0.998	0.011	1.031	0.019	AB
0.936	2.352	0.045	2.847	0.046	2.398	0.029	A C
1.872	2.663	0.251	7.635	0.229	6.567	0.114	ABC

Metal: Olympia **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.496	0.066	0.964	0.016	0.685	0.009	A
0.936	1.986	0.075	2.833	0.436	2.243	0.018	A C
1.872	1.714	0.082	9.023	0.275	7.021	0.144	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: Average Cut(mm/hr)

Metal: Titanium **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.052	0.006	0.051	0.002	0.000	0.000	BC
0.936	0.332	0.042	0.251	0.020	0.087	0.004	ABC
1.872	1.132	0.001	0.957	0.025	0.446	0.029	ABC

Metal: Titanium **Electrode: C3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.086	0.013	0.082	0.003	0.000	0.000	BC
0.936	0.270	0.053	0.371	0.006	0.183	0.009	ABC
1.872	0.630	0.036	1.070	0.015	0.829	0.021	ABC

Metal: Titanium **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.075	0.036	0.095	0.008	0.089	0.001	
0.936	0.196	0.033	0.186	0.008	0.154	0.010	
1.872	0.185	0.025	0.482	0.073	0.438	0.014	AB

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: End Wear (mm/hr)

Metal: Gold **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.207	0.015	0.023	0.006	0.010	0.000	AB
0.936	0.533	0.031	0.113	0.023	0.033	0.012	ABC
1.872	1.413	0.092	0.320	0.020	0.113	0.012	ABC

Metal: Gold **Electrode: C3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.307	0.025	0.100	0.000	0.043	0.006	AB
0.936	0.658	0.020	0.327	0.023	0.100	0.020	ABC
1.872	1.530	0.108	0.847	0.050	0.393	0.012	ABC

Metal: Gold **Electrode: Copper**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.092	0.007	0.027	0.012	0.007	0.006	AB
0.936	1.880	0.060	0.053	0.012	0.020	0.000	AB
1.872	0.467	0.023	0.600	0.040	0.200	0.000	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: End Wear (mm/hr)

Metal: Olympia **Electrode: AF-5**

Average Current	On-Time=4 uSec mean	On-Time=4 uSec SD	On-Time=25.6 uSec mean	On-Time=25.6 uSec SD	On-Time=51.2 uSec mean	On-Time=51.2 uSec SD	
0.468	0.123	0.032	0.000 |	0.000	0.003 |	0.006	AB
0.936	0.367	0.083	0.027 |	0.012	0.000 |	0.000	AB
1.872	0.473	0.046	0.193	0.012	0.007 |	0.012	ABC

Metal: Olympia **Electrode: C3**

Average Current	On-Time=4 uSec mean	On-Time=4 uSec SD	On-Time=25.6 uSec mean	On-Time=25.6 uSec SD	On-Time=51.2 uSec mean	On-Time=51.2 uSec SD	
0.468	0.177	0.040	0.050	0.000	0.010 |	0.000	AB
0.936	0.827 |	0.012	0.173	0.023	0.033 |	0.012	ABC
1.872	0.847 |	0.070	0.493	0.012	0.193	0.031	ABC

Metal: Olympia **Electrode: Copper**

Average Current	On-Time=4 uSec mean	On-Time=4 uSec SD	On-Time=25.6 uSec mean	On-Time=25.6 uSec SD	On-Time=51.2 uSec mean	On-Time=51.2 uSec SD	
0.468	0.047	0.006	0.020 |	0.000	0.000 |	0.000	B
0.936	0.300	0.000	0.047 |	0.012	0.013 |	0.012	AB
1.872	0.793	0.042	0.467	0.061	0.140	0.000	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Positive Polarity)

Parameter: End Wear (mm/hr)

Metal: Titanium **Electrode: AF-5**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.080	0.012	0.003	0.002	0.000	0.000	AB
0.936	0.263	0.029	0.256	0.011	0.008	0.000	BC
1.872	1.028	0.008	0.513	0.044	0.115	0.005	ABC

Metal: Titanium **Electrode: C3**

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.128	0.032	0.032	0.004	0.000	0.000	ABC
0.936	0.317	0.015	0.269	0.008	0.068	0.011	ABC
1.872	0.900	0.018	0.691	0.002	0.305	0.014	ABC

Metal: Titanium Electrode: Copper

Average	On-Time=4 uSec		On-Time=25.6 uSec		On-Time=51.2 uSec		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.067	0.005	0.001	0.002	0.000	0.000	AB
0.936	0.040	0.008	0.011	0.002	0.000	0.000	ABC
1.872	0.177	0.008	0.052	0.008	0.033	0.005	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Negative Polarity)

Parameter: MRR

Metal: AF-5 **Electrode: AF-5**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	61.526	1.078	56.347	0.697	27.345	1.369	BC
0.936	175.124	24.341	170.761	2.813	116.427	7.546	BC
1.872	257.947	2.313	481.945	25.932	352.710	11.363	ABC

Metal: C-3 **Electrode: C-3**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	22.107	1.743	8.339	0.811	4.830	0.668	AB
0.936	91.181	0.212	39.425	4.263	24.218	1.684	ABC
1.872	216.013	7.581	188.009	7.893	92.652	0.612	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Negative Polarity)

Parameter: PEW(%)

Metal: AF-5 **Electrode: AF-5**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	44.452	11.451	93.519	3.297	29.826	1.691	ABC
0.936	50.053	5.341	61.231	1.688	20.089	1.423	ABC
1.872	49.843	0.607	42.148	0.991	15.823	0.611	ABC

Metal: C-3 **Electrode: C-3**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	58.006	0.333	120.817	8.724	721.842	78.826	ABC
0.936	37.103	0.419	87.071	9.634	352.307	40.851	BC
1.872	31.492	2.680	41.447	0.642	219.572	5.204	BC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Negative Polarity)

Parameter: Surface Finish

Metal: AF-5 **Electrode: AF-5**

Average Current	On-Time = 4.0 uSec. mean	SD	On-Time = 25.6 uSec. mean	SD	On-Time = 51.2 uSec. mean	SD	
0.468	1.990 |	0.115	2.453	0.197	2.853	0.133	B
0.936	1.867	0.035	3.410	0.285	4.467	0.287	ABC
1.872	2.413 |	0.339	4.947	0.420	6.800	0.478	ABC

Metal: C-3 **Electrode: C-3**

Average Current	On-Time = 4.0 uSec. mean	SD	On-Time = 25.6 uSec. mean	SD	On-Time = 51.2 uSec. mean	SD	
0.468	1.563 |	0.058	1.357	0.051	1.257	0.023	
0.936	1.977 |	0.197	2.677	0.133	2.367	0.119	AB
1.872	2.677	0.393	5.000	0.409	4.513	0.125	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Negative Polarity)

Parameter: Average Cut (mm/hr)

Metal: AF-5 **Electrode: AF-5**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	3.516	0.062	3.221	0.040	1.563	0.078	BC
0.936	10.008	1.390	9.757	0.161	6.653	0.431	BC
1.872	14.740	0.132	27.542	1.480	20.156	0.649	ABC

Metal: C-3 **Electrode: C-3**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	1.264	0.101	0.477	0.047	0.276	0.038	AB
0.936	5.211	0.013	2.253	0.243	1.384	0.096	ABC
1.872	12.345	0.432	10.745	0.451	5.295	0.035	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

EDM Data
(Negative Polarity)

Parameter: End Wear (mm/hr)

Metal: AF-5 **Electrode: AF-5**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	1.560	0.386	3.013	0.140	0.467	0.046	ABC
0.936	4.960	0.212	5.973	0.129	1.333	0.061	ABC
1.872	7.347	0.083	11.600	0.400	3.187	0.023	ABC

Metal: C-3 **Electrode: C-3**

Average	On-Time = 4.0 uSec.		On-Time = 25.6 uSec.		On-Time = 51.2 uSec.		
Current	mean	SD	mean	SD	mean	SD	
0.468	0.733	0.061	0.573	0.023	1.973	0.083	BC
0.936	1.933	0.023	1.947	0.046	4.853	0.300	BC
1.872	3.893	0.441	4.453	0.189	11.627	0.345	ABC

Vertical lines represent no significance difference between groups in relation to variation in amperage. Letters at the right side of the columns (A,B,C) represent significance difference between groups in relation to variations in the on-time. (Significance difference between 4.0 and 25.6 μSec = A: between 4.0 and 51.2 μSec = B; and between 25.6 and 51.2 μSec = C).

Vita

Guillermo E. Orraca was born on December 9, 1953 to Guillermo E. and Laddie L. Orraca in San Juan, Puerto Rico. He graduated from Gabriela Mistral High School in 1970. He attended the University of Puerto Rico where he completed pre-medical studies in 1973.

The same year he entered the University of Puerto Rico School of Dentistry. In 1977 he graduated Cum Laude, received a Doctor in Medical Dentistry Degree and was inducted into the Omicron Kappa Upsilon Honorary Dental Society.

In September 1977 he entered private practice in Carolina, Puerto Rico. He served as president for the Academy of General Dentistry (AGD), Puerto Rico Chapter from 1978 to 1982. In 1980 the AGD presented him the Membership Recruitment Award. From 1982 to 1987 he served the offices of treasurer, secretary, vice-president and president of the Puerto Rico Dental Society. He completed education and examination requirements for fellowship in the Academy of General Dentistry and received this fellowship in 1987.

In 1989, he accepted a commission in the United States Air Force Dental Corps. He was assigned to Minot Air Force Base in Minot, North Dakota.

In June of 1994 he entered the combined Post-Doctoral Prosthodontic Program at Wilford Hall USAF Medical Center and the University of Texas Health Science Center at San Antonio. In August 1995 he was admitted as a candidate for the Master of Science degree at the Graduate School of Biomedical Sciences. This thesis is submitted in partial fulfillment of a Master of Science degree to be awarded upon completion of requirements, June 1997, from the University of Texas Health Science Center at San Antonio.

He have four children Guillermo (18), Luis (15), Kaylee (15) and Jonathan (10).

He has been assigned the position of Chief of Prosthodontics at Maxwell Air Force Base, Montgomery, Alabama. He will enter this position in July 1997.