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**Review Article**

# A REVIEW ON THE CONVENTIONAL AND WIRE-ELECTRO DISCHARGE MACHINING OF TITANIUM AND ITS ALLOYS

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**ABSTRACT**

Electrical Discharge Machining process became an inevitable and most popular non-conventional machining process due to its capability of machining intricate shape with high accuracy in difficult-to-machine materials. The objective of this paper is to provide a review in the field of EDM and WEDM of titanium and its alloys. The review begins with a detailed introduction on the necessity of EDM and WEDM processes to machine titanium and its alloys and brief overview of EDM and WEDM processes. The various researches are grouped into conventional EDM and WEDM of titanium and its alloys. The area of different researches in conventional EDM and WEDM of titanium and its alloys are discussed.



## INTRODUCTION

Over recent years, materials with superior physical and mechanical properties – for example titanium based alloys, nickel based alloys, metal matrix composites, tungsten carbide and its composites – have been developed due to their wide application area in many engineering fields[1]. These materials are very difficult to machine because these materials are more resistant to corrosion and fatigue, less heat sensitive, harder, tougher and have high elastic stiffness and low density[2]. Nowadays, difficult to machine materials have been widely used in various fields such as aerospace, vehicles, engines, gas turbines, nuclear, bio medical etc. Thus, machining of these materials is major issue in the engineering industries. Since these materials own superior mechanical and physical properties which are useful in many important applications, their machining can discover opportunities which will help to use them more comprehensively.

Among the difficult to machine materials titanium and its alloys are appealing substances in lots of engineering fields such as aerospace, automobiles, engines, gas turbines, nuclear, bio-medical and so on. This is particularly because of their superior mechanical and physical properties which includes: high strength to weight ratio, high yield stress, high creep and corrosion resistivity, high toughness, high wear resistance and desirable bio-compatibility. Therefore machining of titanium alloys has turn out to be certainly one of the most important worries of the manufacturer for the last few decades. Significant researches have been carried out to machine titanium alloys with traditional machining processes [3][4][5][6]. In traditional machining process, Norihiko Narutaki *et al* made an attempt to machine titanium alloys with turning process. They have used various cutting tools such as tungsten carbide tools, cemented TiN tool, ceramic tool, TiC coated tools and CBN tools. The excessive tool wear observed because of high chemical affinity. The carbide tool suffering from large crater wear and severe chipping. Compare to other cutting tools natural diamond shows some improvements in turning of Ti alloy. In the past several years, the development of cutting tools such as coated carbides, ceramics cermet, CBN, silicon nitride and polycrystalline diamond are discovered. But none of these cutting tools have improved the material removal rate and surface finish of titanium alloys. J. F. Kahles *et al* have studied the machining of titanium alloys and the evaluation on the performance of different machining process for titanium alloys have been presented in Table 1.

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**Table 1** Typical parameters for machining Ti 6Al 4V jet engine components (after J F Kahles)[8]

| Operation | Tool Material | Cutting Speed inch/minute | Feed | Depth of cut (inch) |
|---|---|---|---|---|
| Turn (Rough) | C-2 | 150 | 0.010 in./rev. | 0.250 |
| Turn (Finish) | C-2 | 200 | 0.006-0.008 in./rev. | 0.010-0.030 |
| Turn (Finish) | C-2 | 300 | 0.006-0.008 in./rev. | 0.010-0.030 |
| End mill (3/4-1” dia.) | M42 HSS | 60 | 0.003 in./tooth | Axial depth, 0.125 Radial depth, up to Two-thirds cutter diameter |
| End mill (3/4-1” dia.) | C-10 | 200 | 0.005 in./tooth | Axial depth, 0.150-0.200 Radial depth, up to Two-thirds cutter diameter |
| Drill (1/4-1/2” dia.) | M42 HSS | 30 | 0.005 in./rev. | |
| Drill (1/4-1/2” dia.) | C-2 | 40 | 0.004 in./rev. | |
| Ream | M42 HSS | 20 | 0.010 in./rev. | |
| | C-2 | 35 | 0.010 in./rev. | |
| Tap | M7 HSS | 15 | -- | |
| Broach | M3 HSS | 12 | 0.003 in./tooth max. | |
| Spline Shape | M42 HSS | 12 | 0.012 in./stroke | |

In high speed milling tests no regime was found with conventional cutting tools, because at high speeds tool failure happens. Although several researches have been carried out on traditional machining of titanium alloys, most of them discover different tooling material for machining. In all machining process of titanium alloys, the straight tungsten carbide cutting tools have proven their great influence. The interrupted cutting such as tapping, end milling, broaching, planning, drilling and reaming can be performed best by high speed steel tools[9]. P A Dearnley and A N Grearson[10][11] carrying out investigation which have continuous turning of titanium alloys with various tool materials. But in these tooling materials chipping is a major failure of the tools in milling operations of titanium alloys [9].

In order to overcome the technical hitches in machining process of titanium alloys and to achieve dimensional accuracy with intricate shapes, non-traditional machining processes are progressively attempted for machining the titanium alloys. Among the non-traditional machining, Electrical Discharge Machining, Electro chemical machining and Ultrasonic Machining are the comprehensive methods for machining the titanium alloys effectively. In ECM, the characteristic defects such as streaks, pitting and intergranular attack lead to significant decrease in fatigue life. The cost of production also will be higher because ECM process is less cost effective compare to EDM[12][13]. In USM, cavitation streaming and erosion can results in marring of the surface with numerous and deep craters, especially when using intricate form tools with the additional problems of slurry blockage[13][14].Some of the titanium alloys such as Ti 6Al 4V ELI (Extra low interstitial) have been widely used in medical and surgical implants for permanent implant because of their superior bio-compatibility. The proper and appropriate surface treatment requires on the implant surface which improves surface morphology and chemistry for bio-medical application. To produce bio-compatible surface EDM is a probable candidate. The EDM converts the surface into an oxide layer of controlled thickness, which increase the bio-compatibility of the substrate surface and provides a better vehicle for cell attachment and growth also there is no need of surface preparation before EDM[15][16].

EDM is the most important and conservative non-traditional methods for machining titanium alloys with such high mechanical properties. In EDM, the pulse generator generates rapid and repetitive spark discharges which removes the material from electrically conductive materials. There is no direct contact and mechanical forces generate between the tool and the work-piece [17][18]. To machine complex and irregular shapes in various difficult-to-machine materials like titanium alloys WEDM process is used. The WEDM technology is adopted from the conventional EDM machining which is widely accepted non-contact technique of machining. WEDM has discovered from a simple means of making tools and dies to the best alternative of machining micro-scale parts with the highest degree of dimensional accuracy and surface finish quality. There is no physical pressure imparted on the work-piece and amount of clamping pressure required to hold the work-piece is also negligible. Therefore, WEDM has been considered as one of the most effective methods for machining titanium alloys[18][19].

### *Brief Overview of EDM and WEDM process*

### *Working principle of EDM*

The working principle of the EDM process is based on the material eroding effect of controlled electric spark discharges on the electrical conductive work-piece with the help of electrodes. Thus, it is a thermal machining process. The sparks are generated in dielectric liquid between work-piece and an electrode. There is no direct contact between the electrode and the work-piece because material is eroded by electrical discharges[20]. Fig.1 demonstrates that spark take place between the electrode and the work-piece which erodes the material from the work-piece and electrode. Increased sparking gap between the electrode and the work-piece causes another spark to take place at the closest point between the electrode and the work-piece. Each spark leaves a small crater on work-piece and electrode while debris flushed away by the dielectric fluid[21].

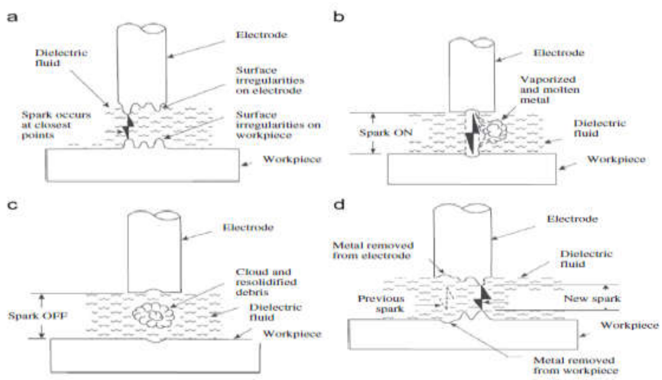


**Figure 1** Different phases in EDM: (a) sparking between work-piece and electrode at closest point (b) melting and vaporization of work-piece and electrode at pulse-on time (c) materials vaporized cloud suspended in dielectric fluid (d) molten metal removal and new [18]

### *Electrical discharge and spark gap in EDM*

The electrical discharge during EDM can be classified into three phases: preparation phase for ignition, Pulse-on Time and Pulse-off Time. The energy channel is created when the gap voltage is applied. The strength of this energy depend on the distance between electrode and work-piece. The discharge takes place in the closest point between the work-piece and the electrode. The insulating properties of the dielectric fluid breaks down by the electric field when electrode approaches to the work-piece. The resistance of dielectric fluid decreases because of the heating generated by electric field and later due to the liberation of debris particles removed as a result of sparking. The electric field turn into the large amount of current flow between the gaps which erode the material. The proper setting of Pulse-on Time and Pulse-off Time helps EDM process to be stable. Furthermore, during the Pulse-off Time the re-ionization happens which result in advantageous condition for the next spark.

***Wire EDM: Principle, Types and Overview***

Wire EDM is unique adaptation of the conventional EDM process which uses electrode to generate the sparks while WEDM utilizes a continuously travelling wire as an electrode. These wire electrodes are made by thin copper, brass, tungsten or molybdenum with the diameter of 0.05 to 0.3mm. WEDM also considered as thermo electrical process in which material erosion produced by a series of sparks between wire electrode and the work-piece similar to EDM process. The work-piece and wire are immersed in dielectric fluid which also acts as a coolant and flushes away the debris[19].

Wire EDM process can be categorized into three types:

- Normal WEDM: In normal WEDM machining is conducted in dielectric fluid which must be electrically non-conductive.
- Dry WEDM: In this method of WEDM machining is conducted in a gas atmosphere without using dielectric fluid.
- Near-Dry WEDM: In near-dry WEDM liquid dielectric fluid is replaced by minimum quantity of liquid to the gas mixture[22].

The evolution of the WEDM process was the result of seeking a technique to replace the machined electrode used in EDM. In WEDM, the guidance of wire is numerically controlled to produce 3D shapes and high accuracy of work-piece. The characteristics of WEDM to machine precise, complex and irregular shapes in various electrically conductive and difficult to machine material makes WEDM a process which has remained as a competitive and economical machining option fulfilling the demanding machining requirements [19].

***Research on the conventional EDM of Titanium Alloys***

***Performance measures in EDM of Titanium alloys***

This section will provide brief overview of EDMing of Titanium alloys and the effect of different parameters on the response characteristics discover by various researches. J. S. Soni *et al* conducted one of the earliest research on rotary EDM of titanium. They have used rotating copper-tungsten electrode on Ti-6Al-4V alloy to investigate its effects on response parameters. They have concluded that MRR improves in rotating electrode while surface roughness and electrode wear rate also increased when speed increasing [23].A research have been conducted on the machining characteristics of Ti-6Al-4V using EDM and USM combined process. The different responses and recast layer investigated through the input parameter variation. They have concluded that higher MRR produced in EDM/USM combination process compare to EDM. The relative electrode wear ratio was smaller when they utilized the distilled water instead of kerosene. They also discover that using kerosene decrease the surface roughness in EDM/USM combination process[24]. Author developed Multiperceptron neural network model with the help of Neuron solutions package to optimize the surface roughness of Ti-6Al-4V. The surface roughness increased with the increasing of current. They identified that voltage of 40V with constant current at 16A gives good surface finish for titanium alloys[25]. Investigation conducted on different input variables and their effect on response characteristics after micro-EDM on Ti-6Al-4V alloy. They developed the mathematical model to represent the relationship of machining parameters. The ANOVA revealed that pulse-on time was the most significant factor for MRR, overcut and taper while peak current had influenced on tool wear rate. Increasing the pulse-on time and peak current increase the effect of MRR and tool wear rate while lower the peak current and pulse-on time decrease the surface roughness[26].The cooling effect of copper electrode on Ti-6Al-4V alloy for electrode wear and SR has been carried out by Suleiman Abdulkareem *et al*. From their investigation they concluded that cooling effect of electrode reduce the electrode wear rate. They also observed the smoother surface finish in cooling electrode effect [27]. Moreover, a study have been carried out to find the effect of duty factor and other input variables on machining characteristics. The result of their study showed improvement in MRR 12%, surface roughness of 19% and electrode wear ratio of 15% which validated with the experimentation[28]. M. M. Rahman *et al* investigated the effect of input parameters on MRR with optimized model. They utilized the Box-Behnken design to obtain optimal response. The investigation revealed that MRR increase when pulse-on time and peak current increases. However, the significance of pulse-off time varies with peak current[29]. Moreover, M. M. Rahman *et al* worked on Ti-5Al-2.5Sn to optimize its MRR in EDM. From their investigation they have concluded that MRR increases with increase of pulse-on time and peak current. They also concluded that increasing the pulse-off time and servo voltage decrease the MRR. ANOVA revealed that peak current was most significant factor for MRR while pulse-off time appears the lowest influence on MRR[30]. Lin Gu *et al* compared the conventional EDM with a bundled electrode EDM on Ti-6Al-4V. From the comparison they evaluated that bundled EDM results higher MRR and lower tool wear ratio than normal EDM. The simulation revealed that bundled electrode with multi-hole inner flushing increase the flow velocity continuously. The peak current, fluid flow rate and the interactions between peak current and pulse-on time were significant on MRR while TWR was influenced by the fluid flow rate and peak current[31]. Research have been carried out on the influence of input parameters on the machining characteristics during micro-EDM of Ti-6Al-4V. The estimated optimum value of process parameters generated through grey relational analysis. They concluded that voltage was most influencing parameter for MRR, TWR and overcut[32]. Furthermore, the research focused on multi process parameter optimization of Ti-6Al-4V had been carried out by VijayVerma *et al*. They investigated the effect of input variables on SR, MRR and TWR. They identified the range of input variables for optimum machining characteristics[33].

***Mechanical properties and Bio-compatibility of EDMed Titanium alloys***

There are many researches have been carried out on the properties of titanium alloys after EDM process. Except on the mechanical properties lot of researches also have been carried out on titanium alloys bio-compatibility due to its wide applications in implant and medical instruments. The thermal effects of EDM process on working material can be predict by simulation. A mathematical model based on heat transfer principles have been developed for simulation by Meenakshi *et al*. They used the Gaussian distribution of the heat source and the temperature-dependent properties of Ti-6Al-4V to perform transient thermal analysis to estimate the crater size and temperature distribution on the work-piece and the residual stress on and near crater. They observed the diameter-to-depth ratio of the crater by simulation and by experiments also. The residual stresses produced were less than 300MPa[34]. Chen *et al* investigated the TiNi based alloy behavior after EDM. From their investigation they observed increasing hardness at near machined surface when pulse duration and peak current were higher. The hardening effects belongs to the formation of oxides in the recast layer[35]. The electrical resistivity of materials is highly dependent on its temperature. If the temperature of material increases it will be result in an increase in material's electrical resistivity.

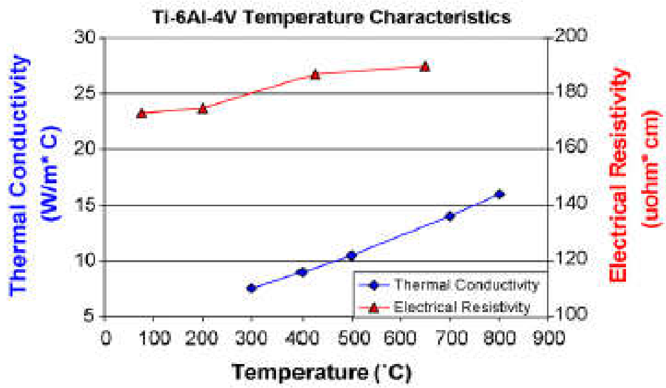


**Figure 2** Electrical resistivity and thermal conductivity vs. temperature for Ti-6Al-4V [36]

To avoid such type of circumstances Peter Fonda *et al* investigated the effect of Ti-6Al-4V's thermal and electrical properties with EDM. They have observed the optimal duty factor for temperature measurements. The duty factor is defined as the discharge on time divided by the sum of the discharge on and off times. The temperature was begins to increase steadily due to certain duty factor which causes poor EDM productivity and quality[36]. In addition, Milos Janecek *et al* investigated the hour-glass shaped samples of Ti-6Al-4V for High Cycle Fatigue tests. From their investigation they observed that induced surface by EDM was sufficient to enhance bone in-growth. They also conclude that the fatigue endurance of EDMed samples were very low because of tensile stress in near-surface regions and formation of micro crack[37].

Josef Strasky *et al* carry forward the above research. They prepared the three different microstructure: Equiaxed, Bi-modal and coarse lamellar from Ti-6Al-4V alloy. They revealed that EDM with high peak current (29A), produces a rough surface with debris, drops and craters. Detailed investigation of SEM showed remnants of the EDM process on the surface which helps to improve the implant-living tissue [38].

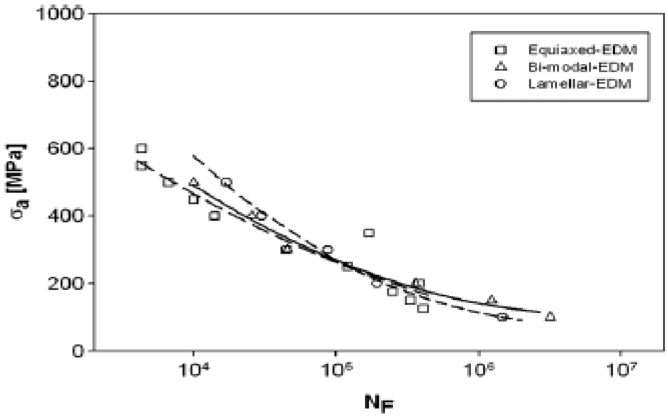


**Figure 3** Fatigue test results: comparison between different microstructures for EDM processed sample[38].

Jana Havlikova *et al* combine EDM, chemical etching and shot peening for surface treatment of Ti-6Al-4V alloy to observe its fatigue life, osteoblast proliferation and viability. They have revealed that shot-peening followed by EDM improve the surface finish and fatigue performance of alloy. Overall, their research showed the significant way to provide the material with favourable mechanical properties and enhance osteoblast proliferation[39]. One of the investigation of fatigue strength of Ti-6Al-4V with surface condition prepared by EDM was carried out by Todd M. Mower. They observed that post-processing with either electrochemical polishing or bead blasting was demonstrated to reduce the deleterious effects of EDM. The investigation showed that modern EDM techniques are capable of processing Ti-6Al-4V with only modest degradation of fatigue strength[40].

***Surface quality and integrity of Titanium alloys after EDM***

Surface integrity is an intrinsic factor which is affected by the machining condition and indicates the machined surface and sub surfaces. Titanium alloys have the ability to meet the requirements of osseointegration thus these alloys are utilised in dental and orthopaedic implants. The surface properties such as surface roughness, surface topography, surface porosity and surface chemistry of titanium alloys have found significant impact on new tissue generation. There are various researches have been carried out on the surface integrity and modification of the EDMed titanium alloys. H. M. Chow *et al* discover a new method of rotating disk electrode for micro slit machining of Ti-6Al-4V. From their investigation they observed that the thermal effect area was smaller and recast layer was thinner with negative polarity. They also found less cracking, less recast layer and a smaller expansion of slit induced with negative polarity[41]. Biing Hwa Yan *et al* investigated the surface modification of pure titanium using an EDM with the addition of urea into distilled water. From their investigation they observed that the surface roughness deteriorated with an increase in peak current and it also became coarser. The TiN was synthesized on the EDMed surface by chemical reaction of the work-piece and the urea solution dielectric fluid. Overall, their research conclude that the surface modification of pure titanium is simple and does not require any special equipment compare to other conventional method[42]. Ahmet Hascalik *et al* performed EDM on Ti-6Al-4V alloy with different electrode materials with different input parameter variation to discover their influence on various aspects of the surface integrity. Their experimental study reveal that the surface integrity of EDMed Ti-6Al-4V includes roughening due to decomposition of recast layer on the surface microcracks, debris and melted drops. The hardness of white layer was higher than the bulk material because of $Ti_{24}C_{15}$carbides. Figure 4 shows the effect of pulse current and pulse duration on surface roughness with different electrodes. There is a relation between surface crack density and white layer thickness [43]. Jianwu Yu *et al* investigated the surface integrity of Ti-6Al-4V alloy after EDM in terms of surface roughness, SEM micrographs and microcracks. From their investigation they concluded that surface roughness was influenced by the thermal properties of alloy and it is necessary to control the discharge energy to avoid worse roughness. The SEM analysis revealed that there were re-solidified metal crystal grains existing on the surface of the specimen but less microcracks induced because of excellent properties of the alloy [44]. A comprehensive study on formation of nanoporous biocompatible layer on GradeIV titanium after EDM was carried out by Pei-Wen Peng *et al*. From their investigation they observed Nano-(γ-TiH) and nano-(γ-TiH and δ-$TiH_{0.71}$) phases were formed by the natural penetration of hydrogen and EDM, respectively. They also reveal that the presence of nano-(γ-TiH and δ-$TiH_{0.71}$) phases on titanium is critical in the preparation of a thick and nanoporous $TiO_2$layer by EDM [45].

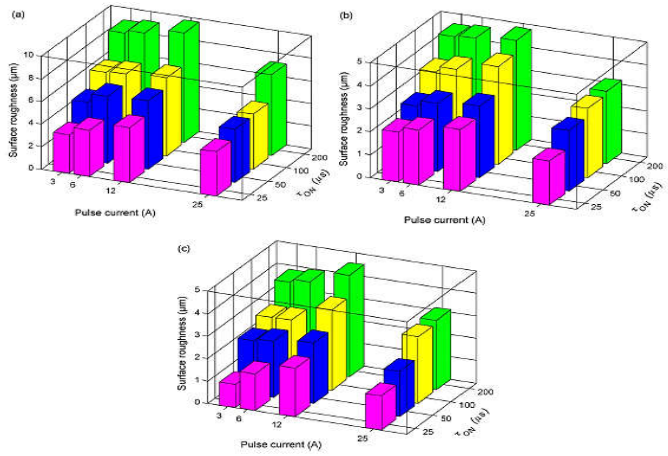


**Figure 4** Effect of EDM parameters on surface roughness of specimens (a) graphite electrode; (b) copper electrode; (c) aluminium electrode [43]

Furthermore, Md. Ashikur Rahman Khan *et al* developed a single order mathematical model for prediction of surface roughness of Ti-6Al-4V in EDM. From their investigation they identified the optimum input parameter for good surface finish[46]. Mohammed Baba Ndaliman *et al* investigated the formation of Nitrides and carbides on Ti-6Al-4V surface with EDM. They utilized the Cu-TaC powder metallurgy electrode and urea solution as dielectric fluid. From their investigation they observed the compound formed on EDMed surface includes nitrides of titanium and tantalum and their carbides. They also obtained the optimal surface topography with less micro-cracks and craters[47]. Furthermore, they carry forward their research and investigated the influence of urea solution and distilled water on the surface properties of Ti-6Al-4V alloy. From their experimental investigation they found that surface roughness was higher when machined with urea solution compare to distilled water. They also concluded that micro-hardness was higher when machined with urea solution[48]. Fei Wang *et al* discover a novel compound machining of titanium alloy with high speed EDM milling and arc machining. From their investigation they concluded that the thickness of heat affected zone was less than 100 µm when peak current was 700A due to low thermal conductivity of alloy. Their study reveals that the compound machining can machine difficult-to-machine materials efficiently[49]. Bryan E.J. Lee *et al* produced three surfaces by varying peak currents. They have observed cell differentiation with pre-osteoblast-like MC3T3-E1 cells in EDM treated titanium alloys. They also observed a contaminant-free titanium oxide layer due to use of titanium as an electrode. Their study demonstrates the potential of using dual topography EDM on titanium as a surface modification technique for implant application[50].

***Powder mixed EDM of titanium alloys***

The powder mixed EDM is extremely used for surface modification of titanium alloys and there are various researches have been carried out on the enhancement of EDM performance by adding conductive or semi-conductive micro-sized and nano-sized powder.

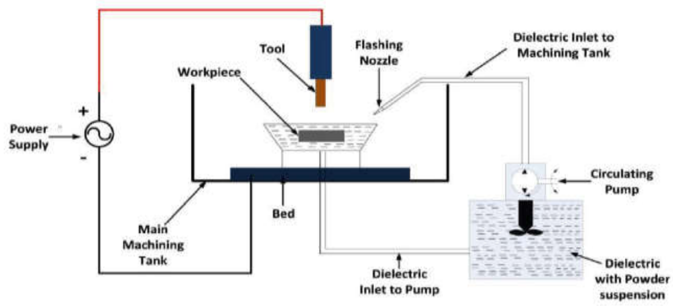


**Figure 5** Schematic Diagram Of experimental setup [51]

To explore the effect of different dielectric fluid during micro-EDM G. Kibria *et al* investigated the effect of kerosene, deionized water and boron carbide ($B_4C$) powder kerosene on the output parameter while machining of Ti-6Al-4V alloy. From the investigation they observed the excellent MRR improvement with larger overcut when dielectric fluid mixing with $B_4C$ powder used while it also increase the TWR compared to pure fluids. The recast layer formation was relatively low when additive mixed dielectric fluid was utilized but it also results in more machining time[52]. Hamidullah Yasar *et al* investigated the effect of SiC powder mixing in water on Ti-6Al-4V alloy surface. From their study they reveal surface integration of the particles were weak for most of the operational range, the particles embedded on the surface depending on the operational parameters[53]. Murahari Kolli *et al* investigated the effect of additives mixed with dielectric fluid on the variation of MRR, surface roughness and tool wear rate on titanium alloy. From the experimental study they observed the increased MRR, SR and tool wear rate while surfactant and graphite powder utilized as additives. They also observed the increasing rate of MRR, surface roughness and tool wear rate while increasing the discharge current [54]. Furthermore, Bhiksha Gogulothu *et al* investigated the effect of graphite powder concentration on PMEDM of Ti-6Al-4V alloy.

From their investigation they observed the increase of MRR and surface roughness when peak current increased. The surface roughness also decreased with increasing the powder concentration. The ANOVA result reveals that the most significant factor for MRR and surface roughness was peak current while powder concentration was less significant [55]. Nihal Ekmekci *et al* investigated the hydroxyapatite (HA) powder suspension in deionized water as dielectric fluid during PMEDM of Ti-6Al-4V alloy. The result of their investigation showed the possibility of HA deposition on titanium alloy surfaces. The result suggest the process as a practical approach for producing biocompatible coatings for medical applications[56]. Murahari kolli *et al* optimized the surfactant and graphite powder concentration in dielectric fluid for machining Ti-6Al-4V alloy. The experimental study reveal the increased MRR with increase in discharge current and graphite powder concentration while increased surfactant concentration also result in MRR increasing. They also observed the surface roughness and recast layer thickness was directly proportional to discharge current, surfactant and powder concentration[57]. B. Kuriachen *et al* performed an experimental investigation to study the effect of SiC micro particles additives EDM on Ti-6Al-4V alloy. They concluded that powder concentration and capacitance were the predominant factors which affect the responses. The maximum MRR and lower TWR were achieved at 5 g/l powder concentration and middle level of capacitance and voltages. They also conclude that the surface coating of Ti-6Al-4V alloy by PMEDM is simple and it does not require any additional tools or process[58]. In addition, Murahari Kolli *et al* carry forward their previous research through the investigation of surfactant and graphite powder additive EDM process. The mixing of aromatic hydrocarbon was taken as surfactant. The EDM with 6.0 g/l surfactant concentration induced the less microcracks and even craters on the surface. The ANOVA results revealed that discharge current and graphite powder concentration influenced the MRR while the discharge current and surfactant concentration influenced the surface roughness and recast layer thickness[59]. L. Li *et al* investigated the SiC abrasive mixed EDM with magnetic stirring on Ti-6Al-4V alloy. They also analyzed the effect of pulse width and peak current on the formation of the recast layer. From their investigation they obtained the smooth surface and clearer boundary of discharge crater in PMEDM. The XRD results reveal that the chemical composition of the strengthened layer contains TiC and $TiSi_2$ phase which improve the micro hardness[60]. To improve the biocompatibility of β-phase titanium alloy Chander Prakash *et al* approached the PMEDM to fabricate sub micro and nano scale topography. The pure titanium was used as an electrode while the pure silicon powder with hydrocarbon oil was used as dielectric fluid to machining of Ti-35Nb-7Ta-5Zr (β-Ti) alloy. From their study they observed that the surface quality was improved due to reduction of micro cracks, crater size and recast layer thickness in silicon powder additives EDM. The thickness of recast layer was influenced by Si powder concentration. The study also reveal that the PMEDM is significant process to fabricate nano-porous biocomapatible surface and it also control the size and density of porosities on the EDMed surface. Overall, they concluded that PMEDM could be considered as potential technique to improve the surface characteristics and chemistry with improved machining efficiency[61].

***Remarks***

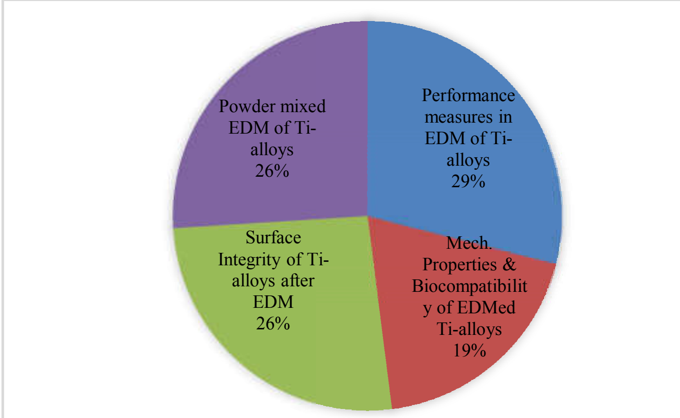


**Figure 6** Research conducted in different areas of conventional EDM of Titanium Alloys

It can be easily realized from Fig. 6 that the most of the researches are focussed on performance measurements of EDM on titanium alloys. These researches are mostly include the various effects of input parameters on response parameters, statistical modelling and optimization of machining process. Another major area of research is combining the different machining, effect of different type of dielectric fluid and powder additives mixed electro discharge machining. The surface integrity of titanium alloys is an important factor to be consider due to its wide applications in dental and orthopaedic implants. There are various researches have been carried out to improve its biocompatibility. The powder mixed EDM is one of the process which can improve the biocompatibility of titanium alloys by improving its surface quality without sacrificing the machining efficiency. Furthermore, very few researches have been carried out on titanium alloys for improving its properties and performance after electrical-discharge machining.

***Wire-EDM of titanium and its alloys***

***Performance measures in Wire-EDM of titanium and its alloys***

In recent years, several researches have been carried out on improving the performance of wire-EDM for machining titanium and its alloys in addition to understanding the effect of input parameters on the response of WEDM on titanium and its alloys. S. Sarkar *et al* investigated the effect of input parameters on response parameters during the WEDM of γ-titanium aluminide alloy. The additive model have been applied to modelled the process and for prediction of responses. They also adopted the constraint optimization and Pareto optimization for optimizing the process. It has been shown that predicted model agreed with the experimental results. The optimized value shown the better productivity with good surface finish and geometrical accuracy[62]. In addition, they carry forward their research to obtain the best cutting speed with good surface finish. In current research they developed a feed-forward back-propagation neural network model for process modelling. From the set of 15625 predicted combinations, 27 optimum combinations selected for effective machining of γ-titanium aluminide alloy. It has been observed that surface roughness increase when cutting speed increases and both values vary linearly [63]. Aniza Alias *et al* investigated the effect of machine feed rate on response parameters during WEDM of Ti-6Al-4V alloy. They conducted experiments with three different machine feed rates values while other input variables kept as constant. It has been observed that machine feed rate plays crucial role in this research work for obtaining low kerf and high MRR. Best combination of feed rate, speed rate, wire tension and voltage were identified[64]. Anish Kumar *et al* investigated the effect of input parameters on four response parameter during the WEDM of pure titanium (grade 2). They modelled these response parameters using Response Surface methodology while optimized with the help of multi response optimization through desirability. The ANOVA results indicated that the quadratic model for machining rate, surface roughness and dimensional deviation were well fitted while pulse on time, pulse off time, peak current and spark gap voltage were most significant factor for responses. It has been shown that high peak current and pulse on time results in formation of craters, pock marks and micro-cracks in surface[65]. Furthermore, investigation of input parameters on response parameters and surface integrity during WEDM of Ti-6Al-4V alloy have been carried out by Farnaz Nourbakhsh *et al*. It has been observed that peak current and pulse width have significant effect on cutting speed and surface roughness. The time between two pulses, pulse width, wire tension and injection pressure influence the wire breakage. They also observed the comparison between high speed brass wire and zinc-coated brass wire which reveal that zinc-coated brass wire was better for achieving high cutting speed with good surface finish[66]. A.V.S Ram Prasad *et al* investigated the effect of input parameters on surface roughness and MRR of Ti-6Al-4V. From their investigation ANOVA revealed that the most significant parameters on both MRR and Ra were found to be Peak current and Pulse on time, whereas pulse off time and servo voltage were less significant factors. Both MRR and Ra increase or decrease simultaneously[67]. J. B. Saedon *et al* studied the effects of different input parameters on different responses through WEDMing of titanium alloy. The effects of the input parameter observed through S/N ratio. They identified the optimal input parameters to achieve minimum surface roughness and higher cutting rate with MRR through combined approach of orthogonal array and Grey relational analysis[68]. P. Sivaprakasham *et al* investigated the influence of various input parameters on response parameters during the μ-WEDM of Ti-6Al-4V alloy. The RSM and genetic algorithm were utilized for optimization while significance of input parameters on response parameters were observed through ANOVA. The optimal values of voltage, capacitance and feed rate for achieving higher MRR and lower SR and kerf width were identified[69]. An experimental investigation have been carried out by Dariusz Poros *et al* towards the efficiency of WEDM for machining of Ti-6Al-4V alloy. They utilized uncoated brass wire, zinc oxide coated brass wire and brass CuZn20 coated brass wire for the experiments. They selected the pulse on time and average working voltage as important WEDM input parameters. They also developed a semi-empirical model selecting the properties of machined materials such as melting point, electrical conductivity, thermal conductivity, thermal expansion coefficient, density and heat capacity. The developed semi empirical model helps in analysis of the influence of material properties on volumetric efficiency of cutting. It has been observed that higher value of thermal conduction and specific heat capacity of material results in decrease of efficiency in WEDM [70]. B. Sivaraman *et al* investigated the material removal rate and surface roughness of Titanium on WEDM. They developed the second order models for MRR using Response Surface Methodology and validated the model using ANOVA and experimentation. The result of this study indicated that all the three machining parameters and interactions of pulse on time and wire tension have significant effect on MRR and Ra. The difference between the predicted and observed value lies in the range of -0.09 to 0.10[71]. Siva Prasad Arikatla *et al* investigated the influence of WEDM parameters on response parameters and surface topography. They made an attempt to optimize the process parameters using response surface methodology. From experimental results ANOVA reveal that the kerf width increases as the pulse on time, input power, server voltage and wire tension increases and the MRR increases as the pulse on time and input power increases. It was observed that as the pulse on time and input power increases, the surface roughness also increases. Further it was observed that as and when the wire tension and servo voltage increases the surface roughness decreases and it improves the quality of machined surface[72].

***Surface characteristics in WEDM of Titanium and its alloys***

Although several researches have been conducted for achieving better surface finish and reducing the defects of surface in conventional EDM of titanium and its alloys, very few researches focused for same achievements in WEDM of titanium and its alloys. An investigation have been conducted by G. W. Qin *et al* towards identification of hydride and its distribution on the surface layer of Ti-46Al-2Cr after WEDM. The X-ray diffraction technique was utilized for the analysis of surface. It has been shown that titanium hydride exist in the surface layer of alloy after WEDM. The WEDM induced micro-cracks have also been observed at much deeper than the recast layer on the surface[73]. Shajan Kuriakose *et al* investigated the surface characteristics and the effect of different input parameter on the surface of Ti-6Al-4V alloy during WEDM. It has been shown that the coated wire were useful to get uniform surface characteristics. The pulse off time was the most significant parameter which influence the formation of layer[74]. An experimental investigation have been conducted by S. F. Hsieh *et al* towards the effect of WEDM on surface characteristics and integrity of $Ti_{35.5}Ni_{49.5}Zr_{15}$ and $Ti_{50}Ni_{49.5}Cr_{0.5}$ alloys. They utilized the X-ray diffraction (XRD) and SEM to observe the microstructure of surface. Due to small value of melting temperature and thermal conductivity, $Ti_{50}Ni_{49.5}Cr_{0.5}$exhibits a rough surface than $Ti_{35.5}Ni_{49.5}Zr_{15}$. The thickness of the recast layer for WEDMed TiNiX alloys decreases with growing of pulse on time. It has been also observed that the hardening effect near the surface region arises due to the formation of the various oxides and the deposition particles of the brass wire electrode in recast layer[75]. Anish Kumar *et al* investigated the effects of different input parameters on surface integrity of pure titanium. The EDX analysis showed the residual of copper, carbon and zinc in the machined surface. The XRD analysis revealed the formation of $TiO_2$, TiO, $TiO_3$, Ilmenite and copper titanium dioxide on work surface. It has been shown that the phase was transferred α to β during melting and resolidification of pure titanium. The SEM results confirm the existence of recast layer but it was less than the die sinking EDM. It has been observed that crater size was larger due to poor thermal conductivity of titanium alloy. ANOVA revealed that peak current and pulse on time were most significant factor for surface roughness[76]. In addition, Anish Kumar *et al* investigated material transfer mechanism in WEDM of pure titanium. The residuals of carbon, copper and zinc were identified in surfaces while utilizing EDX. The XRD tests revealed the migration of electrode and dielectric fluid elements on the surface. It was also observed that pulse on time and peak current weaken the integrity of samples which produces the deeper and wider overlapping craters, pockmarks, globules of debris and micro-cracks[77][78]. An experimental investigation have been carried out by Jinkai Xu *et al* towards analysis of Ti-6Al-4V colored surface through antifriction properties during high speed WEDM. The method of changing the color of surface in high speed WEDM of titanium alloy is due to the electrolysis of emulsion discharge which formed the transparent Ti-film on surface.

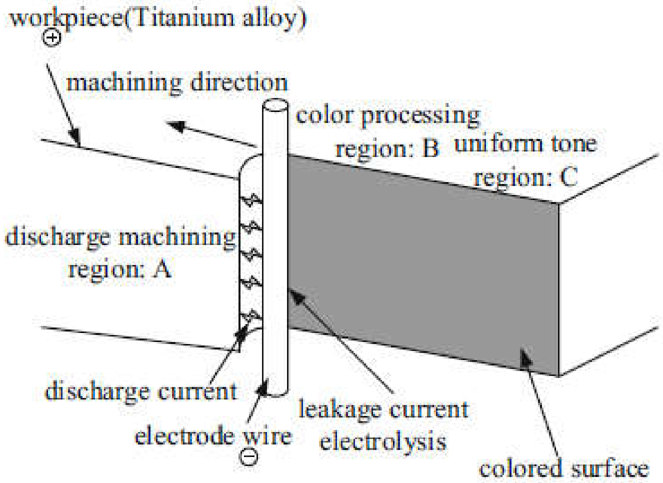


**Figure 7** The coloring process of titanium alloy surface by WEDM-HS[79]

They have fabricated six different colors by adjusting the input parameters on the surface of alloy. It has been shown that the various colors on titanium surface can be prepared with high speed WEDM through changing the input variables and this method is simple, high efficient and low cost consuming compared to traditional methods. This method also improve the durability of surface. It has been observed that friction coefficient was lower in colored surface compared to non-colored surfaces[79].

***Multiple trim cut strategies for WEDM on titanium and its alloys***

In addition, to obtain good surface finish and improvement of surface topography very few researches have been conducted on plausible WEDM mechanism which include rough cut followed by multiple trim cuts at low discharge energy. For instance, D. K. aspinwall *et al* employed multiple trim cut strategies to machine Ti-6Al-4V. The surface integrity and recast layer were analyzed with oscilloscope and ancillary equipment. It has been shown that no apparent recast or damage occur due to multiple trim cut strategy. Furthermore, variation in micro-harness of specimen was observed[80]. An experimental study have been carried out by M. T. Antar *et al* towards surface integrity of Ti-6Al-2Sn-4Zr-6Mo with respect to residual stress using trim cut strategy and clean cut generator technology. They analyzed recast layer, surface micro-hardness and residual stress at near machined surface region using SEM and XRD. From their investigation they have observed that the surface roughness and recast layer thickness could be minimize. They also discover that multiple trim cut strategy is an effective choice to achieve better surface integrity[81]. In addition, M. T. Antar *et al* carry forward their previous research and investigated Ti-6Al-2Sn-4Zr-6Mo titanium alloy using ZnCu50 and Zn rich brass coated wire in emphasis to multiple trim cut strategy. An increase in productivity of 70% and 40% thinner recast layer have been observed while using the coated wires compared to uncoated wires while applying trim cut strategy[82]. An experimental investigation have been conducted by Rupesh Charlisgaonkar towards multiple trim cuts of WEDM for commercially pure titanium. Figure 8 demonstrated the wire offset in multiple trim cut strategy.

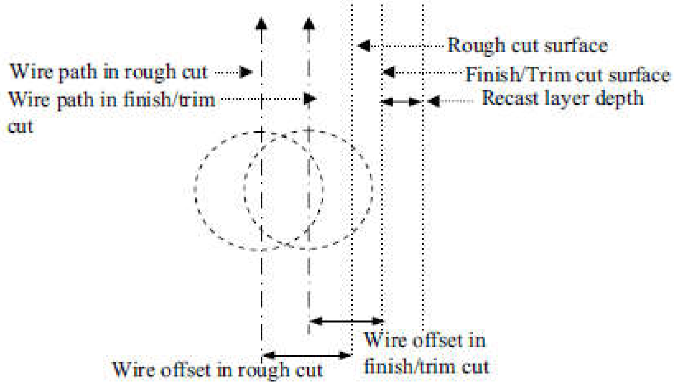


**Figure 8** Wire offset in multiple trim cut[83]

The best surface quality have been observed after finish trim cuts. The craters, debris and spherical droplets were much smaller in finish cut compared to rough cut operation. The EDX analysis revealed that finish cut induced higher concentration of oxygen while rough cut induced Cu contents on work surface[83]. Furthermore, Yadong Gong *et al* investigated trim cut strategy on low speed WEDM for Ti-6Al-4V in terms of surface integrity. It has been shown that micro-cracks induced at edge of micro-voids and debris were deformed on machined surface. Moreover, EDS results revealed Cu and Zn elements found on recast layer. They also observed significant reduction of recast layer after third trim cut. Overall, it has been discovered that trim cut strategy significantly improved the surface characteristics of titanium alloy[84].

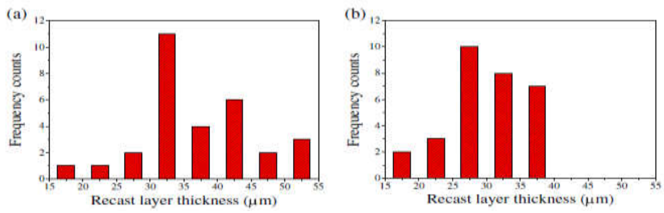


**Figure 9** Recast layer distribution at (a) rough cut and (b) finish trim cut mode[15]

An experimental study on surface morphology, chemical composition and crystallography of the recast layer of WEDM modified Ti-6Al-4VELI have been conducted. The multiple trim cut strategy was evaluated in terms of micro-cracks, pores, recast layer thickness, surface roughness and micro hardness. It has been shown that the finish trim cut has the potential to improve the surface characteristics through the reduction of micro-cracks, pores, SR and recast layer. It has been observed that an $\alpha \rightarrow \alpha'$ + rutile-$TiO_2$phase induced on the recast layer at finish cut. Overall, research reveal that WEDM multiple trim cut have potential to enhance the bio-compatibility of titanium alloy through the formation of rutile-$TiO_2$and amelioration of the surface morphology [15].

***Remarks***

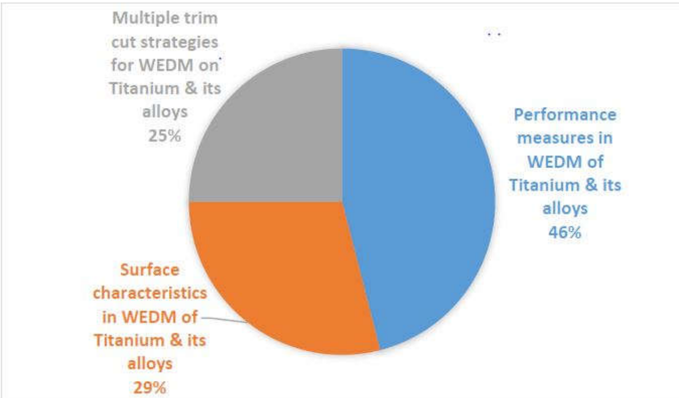


**Figure 10** Research conducted in different areas of WEDM of Titanium Alloys

The WEDM process of titanium and its alloys have various area of researches. The need for intricate shape, mass production, micro-part fabrication and surface modification of these alloys can be significantly satisfied with WEDM. Figure 10 demonstrate that most of the researches have been conducted on performance measures in WEDM of titanium and its alloys. About 29% of the researches focussed on surface characteristics of these alloys in which researcher investigate the effects of input parameters on surface characteristics. Furthermore, various researches have been conducted to improve the bio-compatibility of these alloys. The multiple trim cut strategy is one of the technique of WEDM which can improve the bio-compatibility and surface integrity with higher productivity rate.

**Summary**

Nowadays, to satisfy the increasing demand of intricate shape with accurate dimension WEDM has been discovered as a suitable option. In this paper, a comprehensive literature review of the papers presented by researchers on EDM and WEDM of titanium and its alloys has been presented. The literature survey presented in this paper is classified in different area of research. It has been found from several studies that there are some drawbacks of EDM and WEDM of titanium and its alloys, that need more contemplation in future researches. One of the major disadvantage of using WEDM for titanium alloys is the low MRR and time consuming process, thus it is difficult to utilize in mass production. Another disadvantages of EDM and WEDM of titanium and its alloys are circulation of dielectric fluid, tool wear and comparatively defective and poor surface finish. Future directions of research in the area of EDM and WEDM of titanium and its alloys will continue to overcome these disadvantages and expanding the application of the process for engineering. There are some future research opportunities on the field of EDM and WEDM of titanium and its alloys:

- The EDM and WEDM process behavior on titanium alloys and its comparison with other materials.
- Improvement of the surface finish and characteristics of the titanium and its alloys using multiple trim cut technology and optimization of trim cut process.
- Improvement of the MRR and surface characteristics using different types of additives and their concentration in powder mixed EDM process.
- Optimization of WEDM process of different titanium alloys to fulfill the increasing demand of optimal responses.

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