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Review Article

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# Study the Effect of PMEDM on Surface Integrity of Titanium Alloy Ti-6Al-4V

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## Abstract

Electric discharge machining (EDM) is a cutting-edge machining technique that has been extensively applied to machining difficult-to-cut elements in a variety of industry sectors. It is a non-conventional material removal technology capable of accurately machining complicated forms and morphologies. The EDM method works on the principle of using thermal-electric energy to degrade electrical elements using quickly recurring sparking technique between a non-contact electrode and a titanium Ti-6Al-4V work piece. The MRR (material removal rate) is low and surface finish is poor.to overcome this powder mixed in dielectric fluid is used to increase its conductive strength which is PMEDM (powder mixed EDM). This work provides a thorough evaluation of research investigations on the Electric discharge machining of titanium Ti-6Al-4V workpiece. First, we discuss the characteristics of titanium alloy. Secondly, EDM is discussed with its basic working and types. Next critical analysis of surface integrity in relation to EDM is discussed. Then this work summarizes practical and theoretical EDM investigations targeted at improving process performance, such as MRR, surface roughness, surface morphology, recast layer and residual stress. Furthermore, the study highlights current EDM challenges as well as directions for future research.

## Keywords

Surface integrity, Recast layer, PMEDM, Ti-6Al-4V, Properties

## Introduction

Titanium alloy is extensively used biomedical [1, 2], rapid manufacturing [3], micro-electro thermal models [4], military industry [5], but machinability of titanium alloy as a workpiece is critical. Because of its low thermal conductivities, strong high reactivity, and lower modulus of elastic, Ti-6Al-4V is regarded as a challenging alloy with rapid tool wear during standard machining procedures. As a result, non-traditional machining methods are becoming more common on Ti-6Al-4V. EDM is one of the non-conventional techniques capable of cutting difficult to cut materials.

The primary goal of EDM is to remove the material under the action of successive electrical discharge with a frequency shift. Basic concepts of inventions and discoveries have revealed that it is based on a flow and heat transfer phenomenon governed by heat generated by arc channel and diffused throughout the tool - work [6]. As a consequence, work piece near the channels is removed by melting and vaporization by the dielectric. As a result, EDM is mostly used to remove material from a substrate in order to form 2-Dimensional and 3-Dimensional features. EDM allows for the drills of a wide range of pores (smaller holes, blinds, large, uneven as well as slanted ones) that would otherwise be impossible to achieve with other single processes, particularly whenever the targeted material is titanium alloy. EDM, on the other hand, may be used for more than only bulk material removal [7]. Surface texturing, increase of substrate surface hardness by solidification of electrodes substance, and surface alloys are examples of EDM uses. In EDM, any material with excellent electrical conductivity might be applied as a tool electrode. Materials having greater heat conductivity, melting, and boiling temperatures, on the other hand, are better tool materials. During material erosion, higher pressure and temperature are used, causing the tool to erode as well. As a result, the tool material must have sufficient machine-driven strength to prevent edge faintness [8]. Various tools eliminate substances quickly but have a lot of wear, whereas others have a lot of wear but degrade the base gradually.

## Characteristics of Ti-6Al-4V

Ti-6Al-4V is recognized as a demanding alloy with significant tool wear during normal machining methods due to its poor thermos-physical properties, chemical sensitivity, and reduced elasticity. Table 1, table 2, and table 3 explain the chemical composition of the titanium Ti-6Al-4V work piece along with other metal in %, thermo-physical properties, and mechanical properties, respectively.

**Table 1:** Depicts the chemical composition of the Ti-6Al-4V.

| Element | Weight (%) |
|---|---|
| Titanium | 90 |
| Aluminum | 6 |
| Vanadium | 4 |
| Carbon | <0.10 |
| Oxygen | <0.02 |
| Nitrogen | 0.05 |
| Hydrogen | 0.0125 |
| Iron | 0.3 |

**Table 2:** Physical and thermal property of titanium.

| S. No | Property | Value |
|---|---|---|
| 1 | Density | 4.43 g/cm$^3$ |
| 2 | Specific Heat | 523 KJ/ °K |
| 3 | Electrical Resistivity | 171 μΩ cm at 68 °F |
| 4 | Melting Point | 1674 °C |
| 5 | Thermal Conductivity | 6.60W/mK |
| 6 | Modulus of Elasticity | 105 - 120 GPa |
| 7 | Beta Transus | 995 °C |

Ti-6Al-4V is a non-magnetic dual phase alloy with crystalline structures in both the alpha and beta phases. This high-strength grade can withstand temperatures as low as 800 degrees Fahrenheit (427 degrees Celsius). At room temperature, a Ti-6Al-4V bar must have a minimum yield strength of 120,000 psi to comply with AMS 4928. Titanium may be utilized in either an annealed or a solution-treated and aged state. Titanium bar stock Ti-6Al-4V offers excellent corrosion resistance to a wide range of media, comprising nitric acid in all proportions up to boiling point, saltwater, and alkalis in all concentrations up to boiling point. If chlorine salts are present on strained components that are then exposed to high temperatures, stress corrosion cracking may develop. Ti-6Al-4V has a good oxidation resistance up to 1000 °F (538 °C) [9].

**Table 3:** Mechanical properties of titanium.

| S. No | Mechanical Property | Value |
|---|---|---|
| 1 | Hardness Brinell | 334 |
| 2 | Hardness Rockwell C | 36 |
| 3 | Tensile Strength | 131,000 psi |
| 4 | Yield Strength | 120,000 psi |
| 5 | Machinability Rating | 22% of B-112 |
| 6 | Typical Stock Removal Rate | 30 surface ft/minute |

Hardness of stock is typically 300 BHN. The strength and hardness of the mill-annealed product may be increased by approximately 20% after an aging heat treatment. After aging at 975 to 1025 °F (524 - 552 °C), Grade 5 titanium bar yield strength is 150,000 psi and typical hardness is 360 BHN.

## Application of Titanium Alloy

Titanium alloy, which comes in a variety of shapes and sizes, from bar as well as plate to layer metal and coil. Because of the addition of vanadium and aluminium, crafted and heat handled titanium variations like Ti-6Al-4V are appropriate for higher temperatures and also have good fatigue resilience, lower modulus, high- corrosive resistance, as well as superlative strength/weight ratio. This alloy is frequently utilized in annealed glass or quenched and tempered fan blades, fan discs, front compressors and discs, front compressed air cases and multistage discs, and airframe dies in the aviation industry. Another popular use is medical and dental implants, wherein Ti-6Al-4V has indeed been utilized in implants since the mid-nineteenth century [10]. It's nickel-free, hypoallergenic, and well-tolerated by the body. When titanium is exposed to oxygen, it forms a thin oxide coating that provides excellent corrosion resistance. It is widely used in many industrial processing and maritime conditions, such as offshore oil and gas activities, where it is resistant to pitting and crevice corrosion.

## EDM, EDM-Process and its Categorization

EDM is a non-conventional machining and electro-thermal method that removes material from the work piece using thermo-electric discharges (sparks). The most widely used manufacturing technique in industry is EDM. This strategy is a huge success in a modern manufacturing business and has received a lot of attention. This technology may be used to process either electric-conductive or semi-conductive materials. Because it is a non-contact approach, materials of varying hardness, shape, and toughness can be machined. As a result, EDM may be used to prepare a variety of difficult-to-cut and brittle materials. Dies, punches, and moulds, as well as finishing parts for the aviation as well as automotive industries and surgical components, are all produced using this method. It is used to machine hard-to-machine materials as well as high-strength, temperature-resistant alloys. This method is capable of successfully machining challenging geometries and fragile parts [11, 12].

In 1770, Joseph Priestley was the first to notice it. He was a physicist who was born in the United Kingdom. The different elements are removed from an EDM machine by a sequence of quickly recurrent (repeating) current discharges among the electrodes. Figure 1 illustrates the EDM's basic configuration. A strong voltage is supplied across the dielectric liquid that separates the electrodes. It's used to machine hard-to-process materials with great strength and temperature resistance. Only electrically conducting materials may be machinable with EDM. It can't be utilized without it. The tool electrode is one of the electrodes, whereas the workpiece electrode is the other. The tool is connected to the anode of the power source, while the workpiece is connected to the cathode terminal. EDM can be divided into 2 common types: (1) Sinker EDM and (2) Powder Mixed EDM.

### Sinker discharge machining

The sinker EDM, also known as a die, traditional EDM or Ram EDM. The use of die EDM allows the user to produce complex shapes. This method requires the electrode (usually made of graphite or copper) to be pre-machined into the desired shape and then the electrode is sunk into the article to form a negative of its original shape [13-15].

### Powder-mixed EDM

An improved EDM technique known as powder mixed EDM (PMEDM) adds finely ground, electrically conductive powder to the dielectric. Metallic particles suspended in dielectric reduce the material's insulating properties and, as a result, widen the inter-electrode gap, this enhances EDM performance and produces a superior surface quality compared to traditional EDM [16, 17]. According to the PMEDM process's operating theory, when the proper voltage is applied, an electric field is created that causes the powdered nanoparticles to acquire positive and negative charges. The rapid and zigzag motion of these charged powder particles improves the spark gap among the electrodes. Interlocking occurs between particles moving with the current. This chain aids in bridging the electrode discharge gap, which causes the dielectric fluid's insulating strength to decline and the spark gap to widen [18, 19].

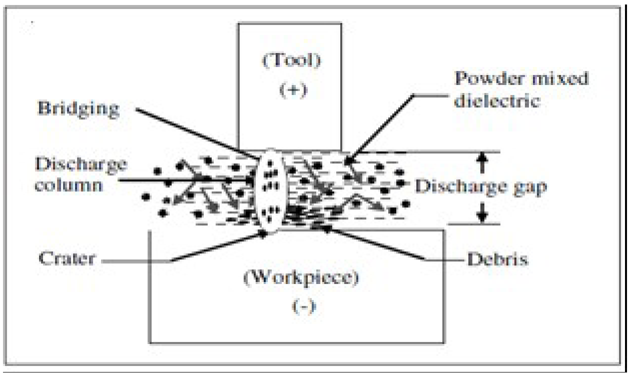

**Figure 1:** Principle of PMEDM process.

In this process suitable materials are in powder form and mixed into the dielectric fluid in the tank. For the better circulation of dielectric fluid by stirring system mechanism. For continued reuse of powder in the dielectric fluid by special circulation system [20]. Various powders of particle that can be added into the dielectric fluid include Aluminum (Al), Graphite (Gr), Copper (Cu), Chromium (Cr), Silicon Carbide (SiC), Nickel (Ni), etc. [21-26]. Spark gap provided by the additive's particles. When the voltage applied between tool electrode and work piece are 80 - 320 V with the gap of 25 - 50 μm and electric field range 105 - 107 V/m were created. The powder material particles get energized and behave like zigzag way in the manner. Under sparking zone, the particles of the material powder come close to each other and arrange themselves in the form of chain like structure between the work piece surface and tool of electrode [27]. An irregularity in the shape and size of powder particles results in interlocking and may lead to chain formation. The bridging effects reduce the insulating strength of the dielectric fluids leading to easy short circuiting and hence early explosion in the gap. A 'series discharge' occurs under the electrode area because of early explosion. The work piece erodes at a higher rate due to quick sparking under the area of electrode. The striking effect of the particles and discharge transitivity increases material removal rate. At the same moment, the added powder enlarged and widened the plasma channel. Even distribution of sparkling among the powder particles leads to reduction in electric density of the spark. Therefore, flat craters are formed on the work piece surface. Hence the surface finish is improved [28].

Tool steel, alloy steel, and especially nickel-based super alloy Inconel-800 has been commonly used as a work piece material by various researchers [29-31]. Other commonly used workpieces in PMEDM are Ti-6Al-4V [32], H-11 Die Steel [33], AISI D2 Die Steel [34], and Hastelloy [35].

## Critical Analysis of Surface Integrity in Relation with EDM

The surface quality of a workpiece is determined by the surface integrity of an EDM surface [36]. From a performance perspective and in terms of determining the life of machined parts, the condition of the workpiece surface is critical. Surface integrity criteria such as surface polish, recast layer, debris etc. are all connected to the quality of machined surfaces in the EDM process as shown in figure 2. This section looks at a variety of surface integrity variables and how to estimate those using numerical and experimental methods with recent publications [37].

The condition of the workpiece and machined surface has a significant impact on the performance and longevity of machined components. Surface integrity should be created for subcomponents or elements produced utilising non-traditional EDM methods, as surface integrity influences the performance of the fabricated surface, lowering efficiency. EDM-machined surfaces have varying levels of surface integrity based on machining different factors including pulse width, current intensity, work piece content, and insulating fluid utilized [38].

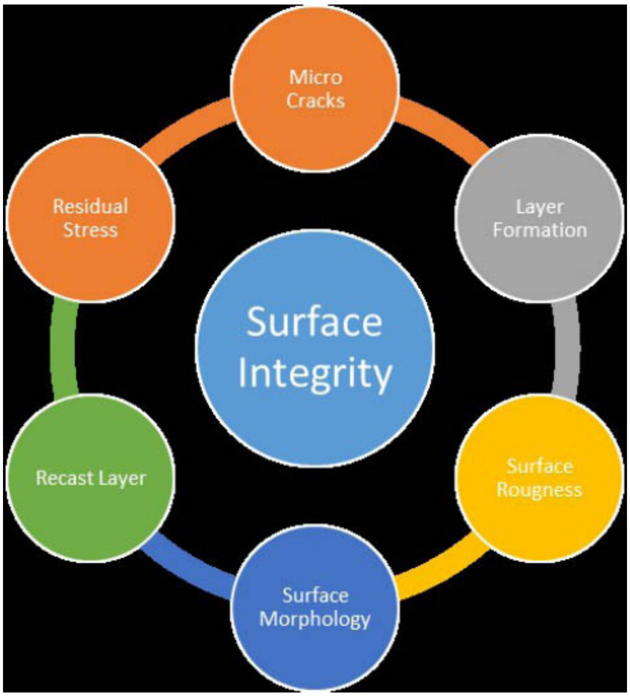

**Figure 2:** Surface integrity parameter.

## Surface integrity discussion considering surface roughness, surface morphology, and residual stress

Surface roughness has an impact on the performance of machined items. Surface roughness in the EDM process is determined by the sparks intensity and craters size created during machining at various discharge currents. The Id (67%), the duty factor (17%), and the pulse length all have a substantial impact on the surface roughness of titanium alloy (14%). Mangesh et al. provides the forecast of surface integrity during the EDM of aluminium-based alloys. Studied the dependent parameter is the response variable, which is the surface feature measure of roughness. The tests were conducted using Taguchi's L18 made by mixing OA's, i.e., orthonormal arrays, that also considers the processing parameters of chemical components, pulse on/off time and current flowing [38].

Pervez et al. [39] investigate the use of PMEDM to coat the properties of titanium (+) ELI medicinal class alloy (PMEDM). In order to grasp desired surface alterations, input parameters such as pulse current, on/off duration, and varied SiC powdered concentrations are employed. The most critical aspect in monitoring of surfacing quality and also the recast layer thinness is powder concentration. A 20 gram/litre concentration of SiC elements results in a considerable reduction in surface fracture frequency and roughness. Surface architecture displays nano-porosity (50 - 200 nm), which promotes Osseo integration by allowing proteins, particularly collagen, to absorb into the surface.

Nguyen et al. [20] classifies the machined surface as a surface layer with a white layer and a recast layer below it known as the heat effected zone. High temperatures, cooling effects, and solidification of molten material all contribute to the formation of such surface layers. The fracture develops and grows into the bulk material attributed to the prevalence of these white layers as well as the recast layer. As a result, caution should be used to prevent the propagation of such fractures, which have a higher rigidity and are fragile naturally, affecting the material's fatigue and surfacing properties. The white layer is good in dental and biological medical uses, but it is hazardous in aviation applications. Nguyen et al. use titanium PMEDM-Sink to increase the quality of the mold's steel surface layer. The integrity of the surface layer was greatly enhanced following PMEDM die sinking-EDM utilizing titanium powder at appropriate circumstances, according to scanning electron microscopy and SR machined surface analysis. Surface layer attributes, such as mechanical characteristics, topographical, and microstructure, were greatly enhanced following EDM using titanium particles mixed into dielectric fluid under ideal circumstances for different mold steels.

## Surface integrity discussion considering recast layer

Titanium alloys, notably Ti-6Al-4V, are widely employed in various high-tech industries, particularly in the aerospace industry, owing to their exceptional characteristics. Machining to reshape this alloy (for example, wire EDM) has an impact on the integrity of the newly formed surfaces due to a variety of variables. One such component that is critical for surface integrity is the recast layer [21-23].

In their experimental investigation, Pramanik et al. [24] used scanning electron microscopy to identify three impacted layers on the cross-sections of a Ti-6Al-4V alloys surface formed by WEDM. The recast layer is generated at a slower cooling rate than the external surface, in which the molten elements resolidify fast and without grain boundaries. The research by Jiajing et al. [25] includes a simulated investigation of the thermodynamic phase shift and shear strength in Ti-6Al-4V, the most prevalent titanium material used in aircraft engines as well as other international corporations, in single-pulse EDM thermo, hydrodynamic, martensitic, and structural dynamics were all incorporated into a multi-physics system. The proposed model was used to investigate the thickness and design structure of the recast layer and heat-affected zone layer. According to ANOVA (analysis of variance) statistics, discharge current has a bigger effect on maximum shear strain than pulse width, while pulse duration has a larger effect on the average length of the recast layer and the deep location of the maximum stress. The findings of this research will aid in determining the authenticity and consistency of EDMed surfaces, particularly when non-destructive analysis is difficult to get.

For PMEDM of titanium alloy, Xu et al. [26] proposed adding $B_4C$ powders to the sparking oil and cooperating with tool-electrodes splashing, which can decrease the thickness of the recast layer and thus increase the machined surface quality. The PMEDM of titanium alloys combined with tool electrode sloshing was performed in this research. The suggested pattern has surface roughness of 20.5 cm was achieved in the titanium workpiece under the action of acceptable process settings, and the recast layer on the workpiece surface was nearly imperceptible. The goal of this work by Bhaumik et al. [27] is to see how process settings and various types of electrodes affect the dimensional accuracy EDMed Ti-5Al-2.5Sn Ti work piece integrity. In this study, the EDM effectiveness of Ti-5Al-2.5Sn metal alloy was compared using various kinds of electrode, including Copper (Cu), Brass (Br), and Zinc (Zn). The EDM surface produced by Cu electrode does have a slimmer and much more consistent recast layer and a higher surface fracture density than the EDMed surface produced by Br and Zn one.

Another research recommends employing multiple types of electrodes [28], such as Cu, Br, and Zn, in EDM to produce grade 6 alloy. The experiment was designed using a response surface methodology based on a face-centered central composite. The Br and Zn electrodes obtain a better MRR than Cu electrodes, according to the results. The Cu electrodes have the least TWR and recast layer, while Br and Zn electrodes have the most. The work of Shirsendu et al. [29] aims to add some value to the existing research by considering their effects on the EDM's surface. The processing is performed by EDM with a cylinder Cu tool and frequent flushes increasing pressures on the Ti named Ti-6Al-4V, and the performance is evaluated to all those achieved with standard kerosene.

## Process Parameters

In the EDM process, there are several input control factors, each of which has its own influence on output responses such as MRR, EWE, surface roughness, and overall surface integrity. These input control variables are listed in figure 2. In EDM, process parameters and regulating elements are important. In general, EDM performance is influenced by the following factors:

A. **Polarity:** This is determined by the electrode and workpiece configurations in order to attain the intended MRR while minimizing surface roughness and TWR.
B. **No-load voltage:** That is the open circuit voltage just before delay interval starts to flow current. It is decided by the producers. The voltage is usually between 60 and 120 V.
C. **Discharge current:** This affects the MRR directly, allowing for better erosion rates with lesser amperes and conversely. Moreover, TWR for Cu electrodes commonly increase with ampere, whereas TWR levels for graphite electrodes do not really increase beyond that amperage.
D. **Pulse duration** is the amount of time it takes a single pulse to discharge or pass current. It happens in microseconds. Corrosion rate, TWR, and surface integrity are all affected.
E. **Pulse interval:** This is the time interval between 2 consecutive pulses. A shorter pulse interval, in general, claims to support lesser corrosion rates that also lowers wear resistance. Nevertheless, a finite quantity of duration time is needed for de-ionization and an adequate decrease in conductivity level.
F. **Gap control:** The operating gap is defined and regulated by the pulse generator's features and parameters. As the discharge energy and pulse-length increase, the working gap widens. The roughness of the increases with increasing as the distance between them grows.
G. **Flushing and circulation rates:** The rate during which dielectric is flushed between both the electrode and the workpiece affects performance significantly. It shouldn't be too big or too small, as this will cause increased electrode wear.

## Identification of Challenges in Existing Approaches and Gap in the Above Literatures

The ideal titanium alloy workpiece should have strong corrosion protection, mechanical qualities, immunogenicity, and controlled degradability in order to be used in a variety of applications. Titanium, a biodegradable substance, is drawing researchers' attention as a potential material for aerospace or implant devices, however it degrades quickly and does not give sufficient mechanical properties. These problems may be solved by employing alloying, mechanical action, machining, and machining parameter optimization. Surface machining and optimization of machining parameters are the subject of this article, which opens up future research opportunities to create more biocompatible materials. The effect of powder size and its concentration on microstructure and recast layer as well as Nano sized powder needs thorough study.

According to the researcher's study, adjusting EDM parameters such as hole diameter, ionic conduction, work piece material, pulse on-off period, and so on, allows for excellent surface integrity. As a result, the scope of future study is explored in this work. In a real-world setting, optimizing machining parameters without accounting for model uncertainty leads to a less precise outcome. However, there are considerable measurement errors when monitoring EDM input parameters. As a result, this study also highlighted the development of more resilient multi-objective optimization algorithms that can manage future uncertainties. Data science, or time series analysis-based optimization, has also emerged as an intriguing study field that might be used to titanium EDM in the future. For analyzing the influence of the EDM process, a substantial portion of previous research work mostly employed the Taguchi optimization technique of parameters. To address multi-objective situations, contemporary EDM optimization techniques need to be enhanced. However, bioinspired optimization approaches are now being applied for multi-criteria decision-making systems in the present situation.

As a result, these methods may be employed to improve the machining of biomedical applications. Several input parameters are used in the machining process. Though the development of a finer surface may be achieved with less uncertainty using appropriate parameters. To accomplish this, multi-objective optimization with lower uncertainty may be used to guide simultaneous maximum of MRR and minimization of surface roughness.

## Conclusion

EDM is a non-conventional method of precision machining that involves electrical spark-erosion among electrodes and the workpiece made of an electrical conductor that is immersed in a dielectric media. The Ti-6Al-4V alloy is difficult to cut and the material may be effectively produced using EDM. PMEDM is an improved process than the conventional EDM technique. PMEDM improves the

MRR, and tool wear rate is reduced as compared to EDM process. Also, it produces mirror like surface finish and the thickness of recast layer is reduced which affects the tool life. High dimensional accuracy is maintained. Surface layer attributes, such as mechanical characteristics, topographical, and microstructure, were greatly enhanced following EDM using titanium particles mixed into dielectric fluid under ideal circumstances for different mold steels. This study investigated how the substance's surface was altered during the EDM procedure.

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## Conflict of Interest

The author declares no conflict of interest that is relevant to the content of this article.

## Credit Author Statement

Anandkumar Nikalje: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft preparation, Writing - review and editing. The author read and approved the manuscript.

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