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Performance evaluation of electric discharge machining of titanium alloy-a review

Rajusing Rathod, Dinesh Kamble and Nitin Ambhore*

*Correspondence: nitin.ambhore@gmail.com

Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, SPPU, Pune, India

Abstract

Titanium alloy has a high specific resistance, excellent machining performance is non-corrosive, and the capability to withstand greater temperatures while maintaining outstanding mechanical properties. This alloy is, therefore, the right choice for aerospace, maritime, biomedical, and industrial applications. But machinability of titanium alloy is challenging as a result of its poor thermal conductivity, highly chemically reactive, and low elastic modulus hence it is treated as a difficult-to-cut material. Fast tool wear is observed during the machining of titanium alloy in conventional machining methods. Therefore, unconventional processing methods are used for the treatment of titanium alloy. Electric discharge machining (EDM) is one of these unconventional machining processes which are used for cutting with high precision, having a high degree of machinability, and getting a better surface finish. It is considered the best choice for machining titanium alloy. In the EDM process, different techniques are used to understand the effects of process parameters such as polarity, peak current, electrode type, pulse on time, and gap voltage on material removal rate, tool wear rate, surface roughness, and wear ratio. This paper critically investigates different types of EDM processes, experimental setups used for machining of titanium alloy, the effect of different tool electrodes and dielectric media on machining parameters, machined surface characteristics, and metal removal rate and tool wear rate.

Keywords: Electric discharge machining, Titanium-alloy, Wire EDM, Die-sinking EDM, Hybrid processes, Surface integrity, Dielectric fluid

Introduction

New challenges in the manufacturing sector, have lead manufacturers to development of reliable and high-quality products as per requirements. Nowadays, to enhance productivity and maintain the surface quality of complex parts, researchers have focused on high-speed machining technologies that involve electron beam machining (EBM), computer numerical control (CNC) machining, chemical machining, laser beam machining (LBM), and electric discharge machining (EDM) [1]. Chemical machining creates a hazardous environment while EBM and LBM need significant investments relative to EDM [2]. Therefore, EDM is the highly preferred machining process to cut very hard materials and worked on the electro-thermal principle [3]. This process is highly popular in manufacturing industries because of its ability to produce desired and complex shapes of rigid materials and alloys and good quality surface finish [4]. Another benefit of the EDM process is the absence of residual stresses due to the method's non-contact character, as there is no physical contact between the working electrode and the workpiece, and thus no cutting forces are generated [5]. In the EDM process, workpiece and electrode are submerged in dielectric media, the desired voltage is generated in the small gap between the workpiece and tool, it formed plasma channels and generates high-frequency electric discharges between the workpiece and electrode [6]. Electrical discharges generate very high temperatures in the range 6000–20000 °C, it melts or vaporizes materials of a tool as well as a workpiece and removed materials from a workpiece [7]. At the end of the process, plasma temperature drops quickly and the workpiece cooled, waste residues in the form of spark erosion are flushed away as debris by dielectric media [8]. EDM is widely used for manufacturing cutting tools, molds, dies [9], bio-implants [10], and sectors such as automobile and aerospace [11, 12]. The principle of spark erosion during the process is shown in Fig. 1.

The performance of the EDM depends upon several parameters and these mainly include pulse-on time and current, voltage, polarity, duty factor, the flushing pressure, and the gap in electrode and workpiece [13]. Over the last few years, several researchers have evaluated the performance of the EDM process for various parameters such as material removal rate (MRR) and tool wear ratio (TWR), and this resulted in machined surface quality. The workpiece and electrode material are the most important factors in determining the performance of EDM parameters. As a result, alternative EDM parameters and electrode materials must be investigated for the microstructure and surface roughness of the machined surface. This paper focuses on different types of EDM processes and various parameters influencing the surface characteristics of titanium aluminium during the EDM process.

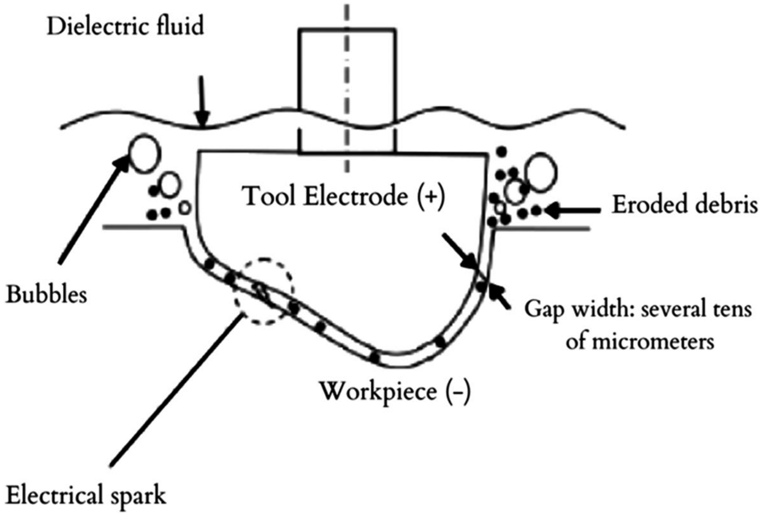


Fig. 1 Spark erosion process [9]

Electric discharge machining

This section provides a brief overview of titanium alloy and tool materials, as well as EDM processes and methods used for titanium alloy machining.

Titanium alloy and cutting tool material

The titanium-based alloys are employed in a wide range of engineering applications such as automobile, aerospace, marine, nuclear, chemical vessels, sports, and medical applications. However, due to their intrinsic mechanical and thermo-physical properties, titanium alloys are considered difficult-to-cut materials with poor machinability. The primary limitations of machining with standard techniques are low thermal conductivity, strong chemical reactivity, and low modulus of elasticity. Thus, non-conventional machining techniques, like EDM, are utilized as feasible alternatives. EDM is a machining process that uses electrical discharge to remove material and produce a desired surface and shape on a specific material or alloy. Many researchers agreed that titanium and its alloys are difficult to machine, are extremely hard, and have a high melting point, making them good material for testing the electrical discharge machining process capability.

Modern industry demands to find the best tool materials or alternate tool materials for machining titanium alloys. To explore the EDM performance of monel 400 alloys, Kumar et al. [14] created copper-titanium diboride electrode material. The finding of their study revealed that 16% titanium diboride gives optimized machining results for material removal rate and tool wear.

Papazoglou et al. [15] conducted several experiments for titanium grade 2 with EDM using graphite electrodes. It is revealed that MRR is mainly affected by the pulse-on current and with an increase of pulse-on current which results in a higher MRR. Fonda et al. [16] presented a machining evaluation of Ti–6A–4V with EDM. They concluded that machining performance depends on the temperature of the workpiece.

Sivaprakasam et al. [17] studied micro-wire electro discharge machining (Micro-WEDM) on titanium alloy (Ti–6Al–4V) with the zinc-coated copper electrode material. The author discovered that as discharge voltage rises surface roughness (Ra) values rise sharply and then fall, and Ra values rise as capacitance rises. They also discovered a fine surface polish at 120 V, 0.1 nF capacitance, and a fixed feed rate of 10 μm/s.

Prakash et al. [18] carried out the electrical discharge machining experiments on titanium grade 2 with brass as the electrode and examined the findings. The result showed that peak current plays a vital impact in the machining of titanium grade 2 material. Kumar et al. [19] conducted a comprehensive overview of different methods used to improve the performance of materials using the EDM process. In their research, it was concluded mixing the powder into the dielectric gives a better surface finish.

Karmiris-Obrataski et al. [20] used a graphite electrode and a high-power EDM during the processing of material Ti–6Al–4V ELI. ANOVA model revealed that both the pulse-on time and current have a strong influence on the MRR with contributions of 61.65% and 21.94%, and provided some combinations of machining parameters that result in a lower TWR and thus lower machining costs, making the machining economically feasible.

Phan et al. [21] examined the surface roughness of machined titanium alloy (Ti–6Al–4V) surfaces using Al and coated AlCrNi electrodes in EDM. The melting point of AlCrNi coated tool electrodes produce a better surface finish with fewer micro-cracks, surface roughness, and voids than uncoated tool electrodes. Jing et al. [22] developed a MIMO adaptive control system for steady and quick electrical discharge machining on titanium alloy. The designed system regulates temperature in the gap between electrode and work-piece rising so fast that the deionization of dielectric liquid and thus produced quality alloy surface.

Abdulkareem et al. [23] investigated the effect of cooling on the copper electrode and process parameters on titanium alloy (Ti–6Al–4V). Liquid nitrogen was introduced as a coolant into the electrode at a temperature of 195 °C and electrode wear was the machinability aspect that was investigated. It is found 27% reduction in EW as compared to EDM of the same material without electrode cooling as pulse off-time and voltage increase to their highest values of 6 μ and 24 V respectively.

Shirguppikar et al. [24] studied the effect of thin-film titanium nitride (TiN) coating on tungsten carbide (WC) micro-electrode on TWR, overcut, and depth of machining in micro-drilling of Ti-6Al-4 V. The experimental findings showed that as compared to an uncoated micro-tool electrode, TWR fell by 16. 32 percent, depth of machining increased by 20. 83% and overcut decreased by 12%.

Mohanty et al. [25] investigated the effect of various micro-tools (brass and tungsten), powder infusion in EDM oil (dielectric liquid), and coating process parameters on the surface modification of Ti-alloy. Parameters like voltage, duty factor, and powder concentration were taken into account while evaluating the micro-hardness, and the surface roughness parameters. It was discovered that sparking occurs more frequently at greater duty factors, resulting in higher surface roughness values. In a comparative analysis, it was found that a detailed study is required to evaluate the tribological properties of the tiny component coated samples and the identification of various intermetallic phases generated on the recast surface is required.

Concerning the above literature, it is observed that research on the machining of titanium alloy has been widely done because it is utilized in numerous applications. With the properties of Ti-6Al-4V alloy, EDM is the best option for its machinability. During machining, the selection of suitable electrodes is very important because it directly influences machining efficiency. According to literature reviews, copper, brass, graphite, copper-tungsten, and tungsten carbide are the popular electrode materials utilized in EDM. Table 1 shows the chemical composition of Ti 6Al–4V (grade 5) and Table 2 shows the thermo-physical characteristics of work and tool materials.

Table 1 Chemical composition of titanium alloy Ti–6Al–4V [4]

Weight (%)	N	C	H	Fe	O	Al	V
Min						5.5	3.5
Max	0.05	0.08	0.015	0.4	0.2	6.7	4.5

Table 2 Thermo-physical properties of work and tool materials [4]

Properties	Tool material				Workpiece material
	Graphite	Copper	Aluminium	Brass	Ti–6Al–4V
Density (g-cm^{-3})	1.77	8.90	2.75	8.73	4.43
Melting point (°C)	3300	1083	660	940	1604–1660
Thermal conductivity (W-m^{-1}K^{-1})	400	385	205	109	6.7
Electrical conductivity (S-m^{-1})	0.3×10^6	59.6×10^6	35×10^6	16×10^6	0.58×10^6

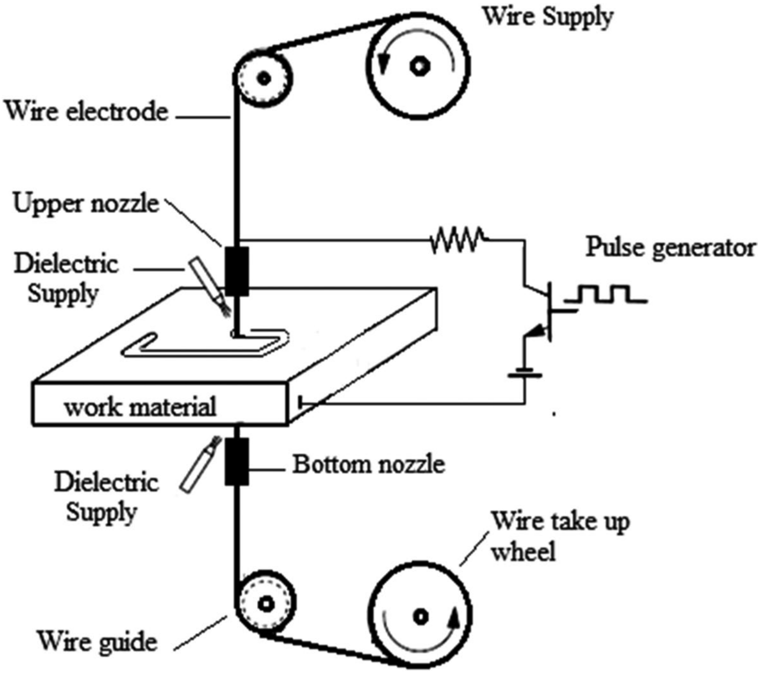


Fig. 2 Basic WEDM Principle [26]

Various EDM processes

With the advancement of the EDM processes, various EDM techniques were developed. The EDM techniques, various processes, and methods used for machining Ti–6Al–4V for evaluating material removal, and surface characteristics of titanium alloy, are presented in this section.

Wire-electrical discharge machining (WEDM)

Wire electrical discharge machining (WEDM) is a type of electro-thermal machining in which material is removed from a workpiece by causing electrical discharges between the wire tool electrode and the workpiece. Because of the circulation of dielectric fluid, the minute chips created by this process are washed away from the working area. The wire tool electrode unwinds on one wheel, which is guided in the correct cutting route, and wraps around another wheel throughout this operation. The minute chips produced by this process are washed away from the working area because of the circulation of dielectric fluid [25]. Figure 2 shows the basic WEDM Principle.

The complexity of the WEDM process has been investigated by several researchers. It is vital to investigate and analyze various aspects and their effects on WEDM processing to obtain the optimum potential processing settings.

Nourbakhsh et al. [26], studied wire electro-discharge machining (WEDM) on Ti6Al4V alloy with the application of different electrodes as high-speed brass wire and zinc-coated brass wire, and the dielectric medium is de-ionized water. In experiment result, in it shows that pulse width and peak current are proportional to cutting speed and inversely proportional to surface roughness. When the duration between two pulses is increased during machining, cutting speed falls, and surface roughness increases. This demonstrates that pulse width and peak current are proportional to cutting speed and inversely proportional to surface roughness. When the duration between two pulses is increased during machining, cutting speed falls and surface roughness increases with an increase in wire tension.

Pramanik et al. [27] used WEDM on Ti6Al4V alloy to investigate parameters such as material removal rate, surface generation, discharge gap, kerf width, and wire degradation. Figure 3 shows a cross-section of a wire EDM-machined Ti6Al4V alloy surface. The outside layers are flaky like an island and discontinuous, while the interior layer is solid with many cracks and holes. The population of flaks fluctuates depending on the machining condition. A shorter pulse on times results in lower surface roughness (4 and 6 ms). There is no substantial variation and manner of surface roughness when the wire tension and flushing pressure are changed. When the pulse rate increases, the kerf widths at the top and bottom of the gap widen. It seems higher at the top than at the bottom when the flushing pressure is lower. When wire tension is increased, the top and bottom kerf widths narrow. It demonstrates that the influence of input parameters on wire form and composition is negligible.

Sivaprakasam et al. [17] experimentally studied the possibility of obtaining super surface polish at the nano level, smaller kerf width, and high material removal rate in machining titanium alloy (Ti–6Al–4V) with the Micro-WEDM process. They concluded that when the discharge voltage rises, the value of Ra rises, and then it falls. It has been observed that capacitance is the most critical parameter influencing the performance of the micro WEDM process. With a capacitance of 10 nF, the entire

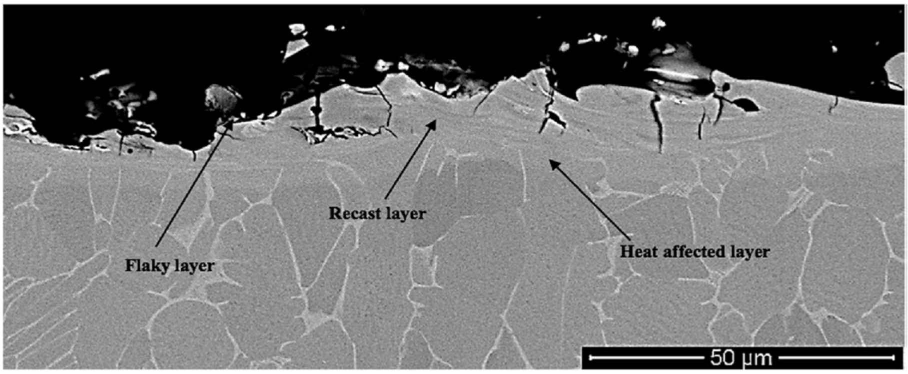


Fig. 3 Typical cross-sectional view of Ti6Al4V surface machined by wire EDM [21]

machining performance of titanium alloy was achieved, with minimal machining time, decreased kerf width, and higher surface quality of less than one micrometer.

It has been observed that several studies have been published in the last year, and many topics have been addressed about the WEDM process. According to the literature, saw-like material cutting with WEDM is quite common in industries and produces very precise and delicate cuts or impressions during production. The researchers' main goals are to improve the performance and broaden the application possibilities of the WEDM method. The future goals are to identify new ways to apply new versions of the WEDM process and to use these processes on materials that are discovered in the future. Further efforts are required to optimize WEDM processing to meet the requirements of the Industry 4.0 stages.

Die-sinking EDM

In contrast to WEDM, die-sinking EDM employs an anticipated die to replace the wire in the former case. Die-sinking EDM finds a better option to machine difficult profiles in titanium alloy. Similar to WEDM, the mechanism of die-sink EDM is also controlled by the properties of the workpiece material. In this process, the workpiece is mounted on the table of the machine tool and the electrode is attached to the ram of the machine. A DC servo unit moves the ram and electrode vertically while maintaining the electrode's proper position about the workpiece. The servo mechanism and power supply control the positioning automatically and with exceptional precision. The electrode never touches the workpiece in normal operation but is separated by a small spark gap. The ram drives the electrode toward the workpiece until there is enough space between them for the voltage in the gap to ionize the dielectric fluid and allow an electrical discharge or spark to travel from the electrode to the workpiece. Figure 4 shows the EDM die-sink process [29].

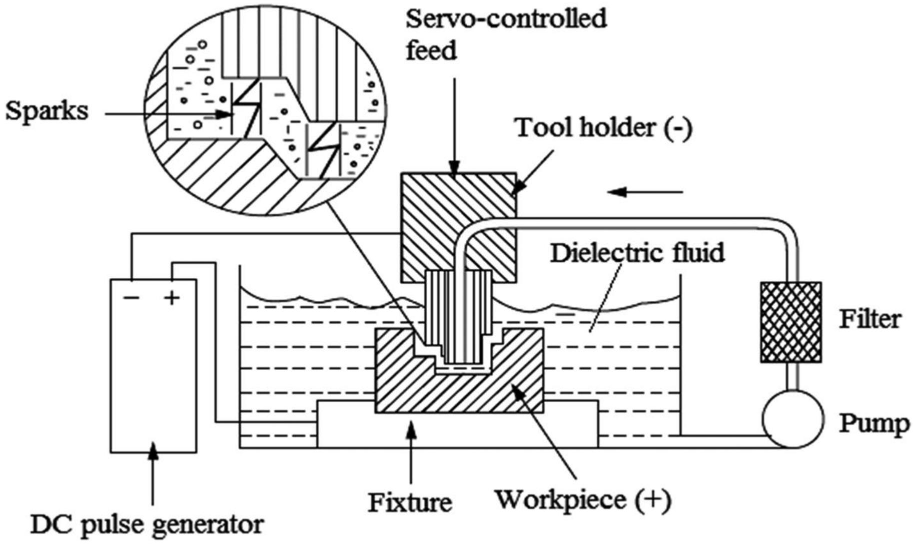


Fig. 4 Schematic of an EDM die-sink process [28]

Rahman [30] has created an ANN model for estimating output as TWR, MRR, and SR utilizing an EDM die-sinking machine for cutting Ti–6Al–4V. They used the radial basis function neural network (RBFN) model to create the ANN model and discussed the relationship between sensitivity and input parameters. It observed peak current has the greatest impact on performance indicators. The best surface roughness is achieved with a peak current of 15 A, a servo voltage of 95 V, a pulse on time of 85 µs, and a pulse off time of 232 µs. Zainal et al. [31] examined the dimensional accuracy (DA) of Ti–6AL–4V during die-sinking electrical discharge machining (EDM) with positive polarity copper-tungsten electrode. They created a mathematical model to investigate the impact of cutting parameters on workpiece dimensional correctness. The importance of cutting parameters was determined using the Analysis of Variance (ANOVA) technique. They concluded that the most critical criteria that determine DA are pulse on time, pulse off time, peak current, and servo voltage. Hascalık and Caydas [32] tested graphite, copper, and aluminum electrode materials for die-sinking EDM machining of Ti6Al4V, and found that graphite electrode has the highest MRR, followed by copper and aluminum electrodes.

From the above literature, it was discovered that more emphasis should be placed on electrical properties in this area, with various parameters such as peak current, pulse width, and off-times requiring further investigation during machining. Other significant effects of the Ti6Al4V die-sinking process must also be investigated.

EDM ultrasonic and laser-EDM

To improve machinability, the hybrid machining method combines conventional EDM with other technologies. The basic goal is to reduce the drawbacks of a given process by incorporating another process. With the use of ultrasonic, laser, and magnetic fields, the EDM method has been successfully employed to improve machinability on titanium alloy [26]. Mugilan et al. [33] used hybrid micro-electrical discharge machining to experiment with various vibration frequencies and dielectric combinations on Ti–6Al–4V to optimize the machining process and eliminate the negative impacts of residues accumulated in drilled holes. The material removal rate improved when the pulse off time was increased in a hybrid micro-electrical discharge machining kit that was devised and implemented. Figure 5 shows schematic diagram of die-sinking electrical discharge machining with vibration kit.

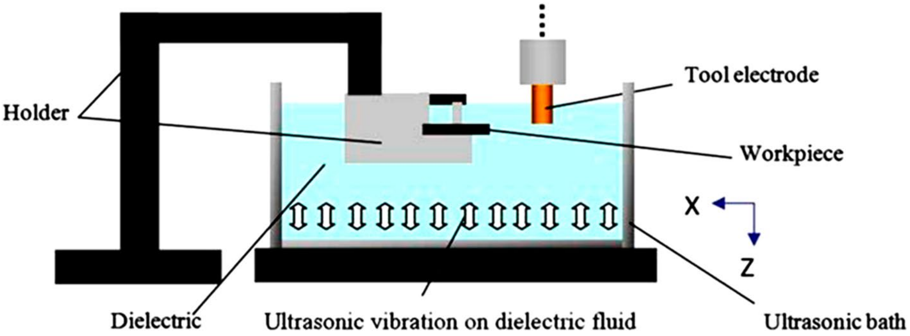


Fig. 5 Ultrasonic vibrating set-up [34]

Researchers have conducted extensive research to increase slurry circulation, injection or suction through an electrode or workpiece holes. Despite that, these are not performing easily and generate defects on the workpiece. Several strategies have been developed to minimize unwanted impacts when modifying structures. The use of ultrasonic vibration electrical discharge machining improves these results. The use of ultrasonic vibrating movement on the electrode improves slurry circulation in this procedure. The debris was forced away and a new dielectric was pulled in by the high-frequency pumping action. It improves machining efficiency and yields a higher removal rate.

Kremer et al. [34] investigated ultrasonic vibrations and their impact on EDM performance. After comparing operations with and without ultrasonic vibrations, it was discovered that with ultrasonic vibrations in the electrode, the process improved. The high-frequency vibrating electrode accelerates slurry circulation, resulting in machining times for finishing processes that are typically 5 times shorter. The significant pressure changes in the gap are found to provide efficient discharges that remove more debris from each crater and increase the surface layer, thermal residual stresses, few micro-cracks seen, and fatigue resistance is improved by up to 6 times. It demonstrates that the process is stable when there is a small gap. As a result, combining EDM with USM can improve the manufacturing of complex shapes. Chen et al. [35] discovered that using ultrasonic vibration in EDM machining on Ti–6Al–4V alloy improves material removal rate and results in better-machined surfaces. Because of the regulated discharges at specific locations and the creation of minute debris, the alloy’s overall machinability has improved.

Zhang et al. [36] worked on SiC abrasive particles in ultrasonic-assisted EDM milling to improve the surface quality and reduce surface fractures. Wansheng et al. [37], employed an ultrasonically vibrating tool electrode in the EDM process to help drill deep and small holes in titanium alloys, which was previously thought to be a difficult approach due to low heat conductivity and strong tenacity. Singh et al. [38] performed an in-depth parametric analysis on Ti alloy μ-USEDM by using a tungsten carbide electrode. It was discovered that as the ultrasonic power is increased, the tool wear and taper angle of the drilled hole decreases progressively for a given EDM parameter.

Shabgard and Alenabi [39] studied EDM of Ti–6Al–4V alloy with copper tool vibration at ultrasonic frequency and its impact on output parameters. Experiments were performed on die-sinking EDM and planned as per the full factorial design of experiments (DOE) method. During experiments, it was observed that the rate of material removal in US-EDM was significantly higher than in conventional, induced high dielectric flow which helps to clean gap distance. Tool wear ratio is lower in US-EDM and it was less in short pulse duration than in EDM, but it happened inversely as the duration of pulses rises. This study found that ultrasonic vibration of an EDM tool in finishing modes increased MRR and decreased TWR considerably.

Because of its flexibility and accuracy, as well as its ability to cut practically all materials, laser machining is a significant tool for the production of micro features in materials. We can combine laser-cutting technology with high-speed electrical discharge machining when high accuracy and metallurgical quality are required (EDM).

Al-Ahmari et al. [40] evaluated the feasibility and uniqueness of a hybrid method by machining micro-holes with a diameter of 200 mm in Ni–Ti-based SMA using a combined laser and micro-EDM drilling process. Using laser and micro-EDM, a new hybrid machining technique was devised. Micro-holes are first laser-machined for maximal material removal, then ringed by micro EDM drilling to save time while maintaining dimensional precision and surface quality. A revolutionary hybrid machining method reduces machining time by 50–60% and increases MRR by 46–65% without compromising micro-hole quality. Prihandana et al. [41] investigated the effect of micro-powder suspension and ultrasonic vibration of dielectric fluid in micro-EDM processes. The results showed that the introduction of MoS_2 micro-powder in dielectric fluid and using ultrasonic vibration significantly increase the material removal rate and improve surface quality by providing a flat surface free of black carbon spots.

The summary of contributions of the previous researchers has been presented in Table 3.

Performance measures of EDM

Material removal rate and tool wear rate

MRR is one of the key parameters considered in EDM. It has a direct impact on product quality, productivity, and cost-effectiveness. The MRR is the rate at which material is removed from a machined component in a given amount of time during the machining process. MRR is determined using Eq. 1 [15].

Table 3 Summary titanium alloy by EDM process

References	Process used	Workpiece materials	Tool material
Ref. [1]	Powder mixed EDM	Ti–6Al–4V	Graphite
Ref. [2]	Ti-6Al-4V	Ti–6Al–4V	Cu-TaC composite electrode
Ref. [4]	EDM	Ti–6Al–4V	Aluminum, brass, graphite and copper
Ref. [6]	EDM	Titanium grade 4	Copper
Ref. [7]	EDM	Titanium carbide (TiC)	Copper
Ref. [8]	EDM	Ti–6Al–4V	Tungsten carbide electrode
Ref. [12]	Micro EDM	Ti–6Al–4V	Copper
Ref. [13]	Powder-mixed EDM	Tantalum alloys	Graphite
Ref. [14]	EDM	Copper–titanium diboride powder metallurgy electrode	monel 40 material
Ref. [16]	EDM	Ti–6Al–4V	Copper
Ref. [21]	EDM	Ti–6Al–4V	Al and AlCrNi coated Al electrode
Ref. [23]	EDM	Ti–6Al–4 V	Copper
Ref. [30]	EDM	Ti–6Al–4V	Copper
Ref. [31]	Die-sinking EDM	Ti–6AL–4V	Copper-tungsten
Ref. [32]	EDM	Ti–6Al–4V	Graphite, electrolytic copper and aluminium
Ref. [39]	Ultrasonic-assisted electrical discharge machining	Ti–6Al–4V	Copper
Ref. [42]	EDM	Ti–6Al–4V	Brass
Ref. [43]	Powder mixed EDM	Ti–6Al–4V	Pure titanium
Ref. [44]	EDM	Ti–6Al–4V	Brass
Ref. [45]	EDM	Ti alloy	Graphite
Ref. [46]	EDM	Titanium grade 2	Brass

$$MRR = \left(\frac{W_i - W_f}{p_w t}\right) \tag{1}$$

Where W_i is the initial weight of the workpiece in grams, W_f is the weight of the workpiece after machining, p_w represents the density of the workpiece and t is the machining time in minutes. TWR is another key parameter widely used to evaluate the performance of EDM. It is the ratio of the volume of material removed from the electrode to the volume of material removed from the workpiece and is calculated by Eq. 2 [15].

$$TWR = \left(\frac{E_i - E_f}{p_e t}\right) \tag{2}$$

Where E_i is the electrode weight before machining in grams, E_f is the electrode weight after machining in grams, t is the machining time in minutes and p_e is the density of electrode material. Extensive literature is available relating to the effect of process parameters on the performance of EDM of the titanium alloy. The performance of EDM is evaluated by MRR and TWR [6]. Accordingly, Ishfaq et al. [42] studied the influence of electrode materials, tool polarity, servo voltage, flushing time, pulse–time ratio, and current on the output response in terms of MRR and TWR for Ti–6Al–4V. The finding revealed that the maximum MRR (7.602 mm^3/min) was achieved with graphene mixed dielectric (64.5%) which was greater as compared to that obtained with kerosene (4.621 mm^3/min). But, the minimum TWR obtained for graphene-based dielectric (0.17 mg/min) is approximately 1.5 times less than that achieved with kerosene. The minimal magnitude of TWR is observed with the positive polarity using a copper electrode in a graphene-based slurry. Alam et al. [1] investigated the performance of power mixed EDM in the machining of Ti–6Al–4V in terms of MRR and TWR. The study adopted surface response methodology to investigate the influence of process parameters including peak current, powder type, and powder concentration on MRR, TWR. The result showed that TiO_2 powder has a much higher (3.42 times) effect on MRR compared to graphite powder, and for MMR, it was observed 1.73 times lower compared to that of graphite powder.

Furthermore, Singh et al. [47] conducted an extensive literature survey related to dielectric fluids and their effect on MRR. The authors concluded that metal partials in dielectric fluids reduce the insulating strength of the dielectric fluid and increase the spark gap between the tool and workpiece. As a result, the process becomes more stable, and the metal removal rate and surface finish increase. Abdudeen et al. [48] studied a different aspect of mixing various powders such as silicon, aluminum, graphite, chromium, nickel, and silicon carbide micro powder with the dielectric media. The authors concluded that the powder-mixed EDM process improves the performance in terms of MRR and surface. Suresh et al. [29] studied several types of dielectric fluids and their use in the EDM process. Dielectric medium is considered as de-ionized water or tap water, hydrocarbon oils, kerosene, mineral and transformer oil, gas, and a mixture of liquid and gas. The machined surface shows fewer defects. The use of powder-mixed EDM and composite electrodes helps to create a defect-free surface.

Devarajaiah and Muthumari [43] investigated the effect of machining parameters including pulse-on-time, pulse-off-time, current, and wire-speed on the material removal rate. The authors reported wire speed and current were the significant variables to MRR of Ti–6Al–4V however the pulse-off time was found insignificant. Gu et al. [44], studied the Ti–6Al–4V electrical discharge machining process with a bundled die-sinking electrode. A 3-factor, 3-level experimental design was adopted to study the influence of MRR and TWR on fluid flow rate, peak current, and pulse duration. The tool wear is pointedly influenced by the rate of dielectric flow and peak current in die-sinking EDM. The effect of pulse on-time, flushing pressure, and tension in wire on MRR while WEDM of titanium alloy showed in Fig. 6.

Other research investigations looked into the machining characteristics of titanium alloy. For example, Kolli et al. [45] studied the machining characteristics of titanium alloy in the wire EDM process, and, in another investigation [50], the effects of machining parameters on the performance parameters in EDM of titanium alloy were studied.

Surface integrity

Surface integrity refers to the overall appearance of the surface as well as the numerous machined surface characteristics including surface roughness, residual stress geometric, crack density micro-hardness profile, etc. These characteristics are very important components performance, durability, and reliability. Many research studies were published to investigate the use of the EDM technique in surface treatment, and found that the surface was improved [1, 27, 47].

Suresh et al. [29] investigated the effects of surface hardness and roughness, as well as the rate of surface wear on the electrode and the metal. Three electrodes, namely copper, graphite, and brass, were used to create the comparison results. Three elements, namely electrode material, spark gap, and depth of cut, are used to develop an experimental design at three levels (3^3) surface roughness, surface hardness, and dimensional differential. Input factors and responses were recorded for each run of the experimental design. Statistical software was used to examine the recorded data. The impact of each input parameter on each response, as well as their correlations, is illustrated below.

Figure 7 indicates that surface roughness is lowest when machined with fewer spark gaps and shallower depths (experiment runs 1, 4, and 7) for the above three-electrode materials. Figure 8 shows the deviation of points from the starting hardness reference

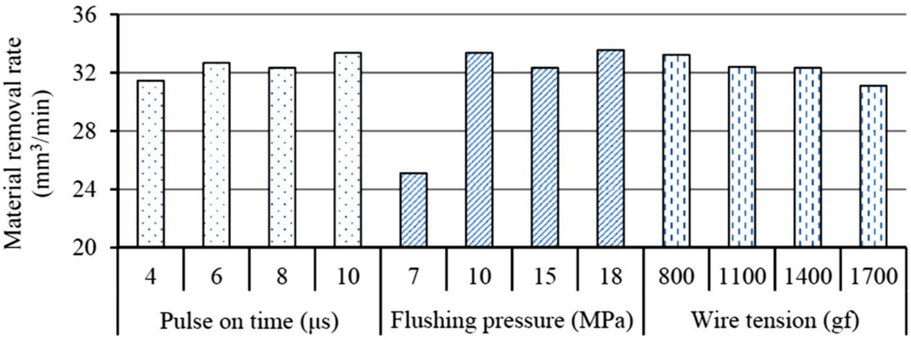


Fig. 6 Influence of pulse on-time, flushing pressure and tension in wire on MRR while WEDM of titanium alloy [49]

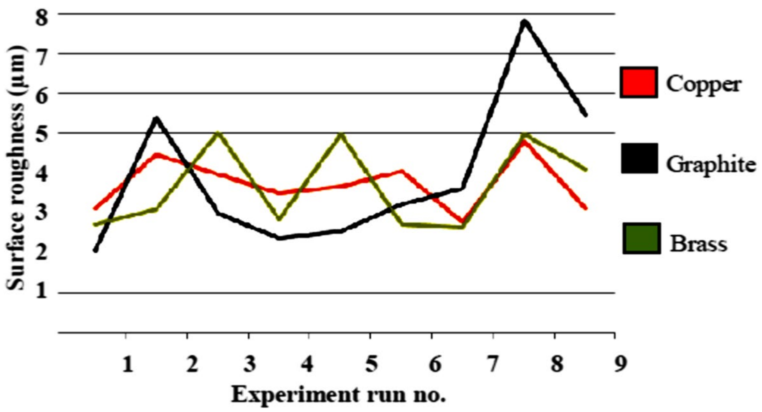


Fig. 7 Surface roughness comparison [29]

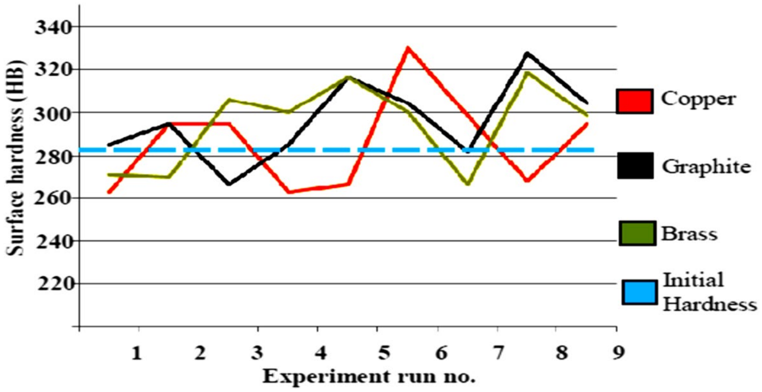


Fig. 8 Surface hardness comparison [29]

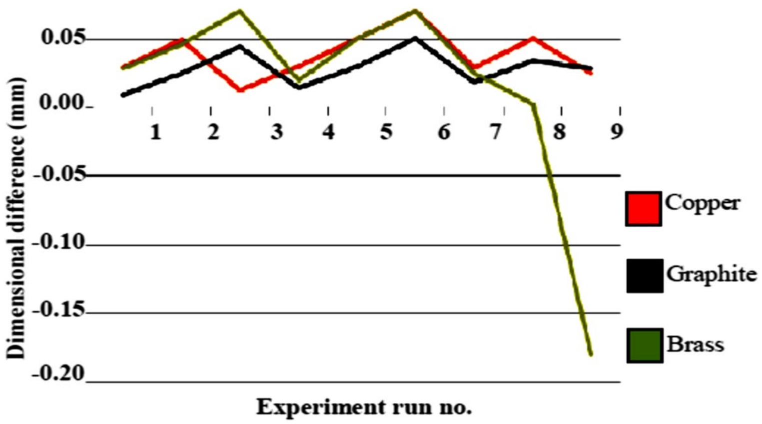


Fig. 9 Dimensional differential plot [29]

line (blue dash line), indicating a non-uniform pattern of deviation, and the Fig. 9 shows that the graphite electrode is the most efficient of all electrodes, with plots that are very close to 0 when compared to brass and copper plots. The research demonstrates that graphite performs better in EDM die-sinking machining on Ti6Al4V with three electrodes, and this performance is attributable to graphite's superior electrical characteristics.

Kumar and Davim [46] investigated the powder mixed EDM process which concluded that surface quality drastically increases at a high machining rate. Rupesh and Jatinder [51] studied the surface integrity of wire and work specimen in WEDM of titanium using brass wire. The process variables considered were pulse on time, pulse off time, applied current and wire current, wire offset, and wire feed rate. The finding raveled that lower values of pulse on-time and wire offset were found to yield the best surface quality with zinc-coated wire electrodes.

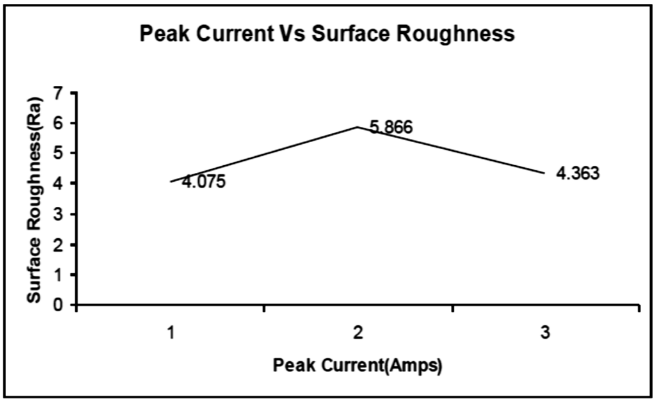
In another study, Alias et al. [52] reported that the variation in surface topography is minimal concerning wire feed rate. When MRR is lower, a comparably smoother surface is obtained. Surface quality degrades as cutting speed increases almost linear with a surface roughness of 2.44 μm at 2.65 mm/min machining speed. Surface roughness deteriorates dramatically as machining speed is increased above this point. Pulse-off-time does not affect the surface finish or dimensional inaccuracies.

Surface qualities play a key and extremely important function in new bone production and future tissue growth, according to Schwartz et al. [53]. During in vivo and in vitro studies, surface features such as surface roughness, surface topography, surface porosity, surface chemistry, and surface energy were discovered to have a substantial impact on new tissue creation and collagen or protein absorption.

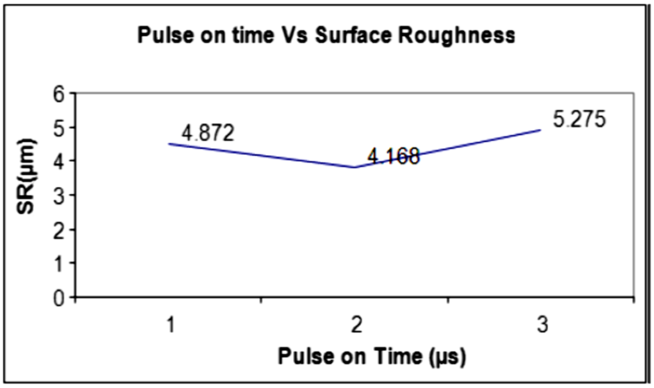
Opoz et al. [54] worked on Ti–6Al–4V (grade 5) for surface improvement with hydroxyapatite powder mixed electrical discharge machining using titanium electrode and deionized water dielectric fluid. Machining condition was selected as 22 A pulse current and 12 μs pulse on duration. The experiment showed that PMEDM-made surface features have specific features and morphologies as compared with EDM-made surfaces without powder in deionized water. EDM-made surfaces show the development of smooth molten materials and relatively shallow craters, indicating a lower average roughness and when the concentration is raised, the surface roughness increases. It observed that EDM-made surfaces consist of a few micro-cracks when the machining process used only demonized water.

Sabitha [55] studied the impact of process parameters on surface roughness on Ti–6Al–4V during EDM. The effect of various input parameters such as pulse on time, current, and level of a gap on the surface roughness Ti–6Al–4V (Figs. 10a and 11c). Authors observed that surface roughness increased with an increase in the peak current to ascertain the level of current and afterward the surface roughness decreased even though the increase in peak current. Also found surface roughness decreases as an increase in pulse on time up to a certain level and afterward surface roughness increases as an increase in pulse on time. Regarding the level of a gap, the authors found that the surface roughness increases as an increase in the level of the gap.

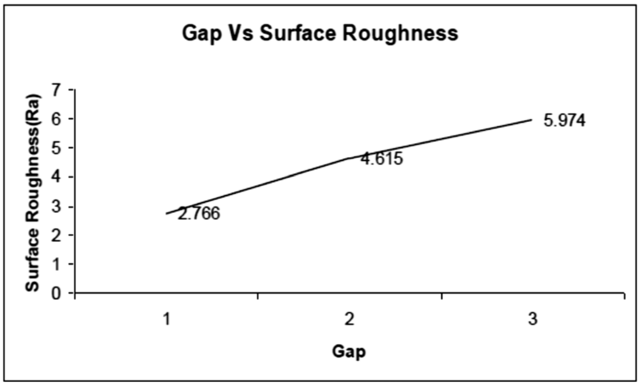
Chakraborty et al. [56] presented the performance of Ti–6Al–4V by mixing the powder in different dielectrics during WEDM. In the first stage, the experiment was conducted using a brass electrode of diameter 0.25 mm. with two dielectric fluids such as deionized water and kerosene. In the second stage, experiments were performed by mixing surfactant Span 20 (chemical composition = $C18H34O6$) in these dielectrics. The study focused on the effects of four input parameters on MRR, SR, and dielectric



(a) Influence of Current on surface roughness [38]



(b) Effect of Pulse on time on surface roughness (SR) [38]



(c) Effect of Gap on surface roughness [38]

Fig. 10 **a** Influence of current on surface roughness [37]. **b** Effect of pulse on time on surface roughness (SR) [37]. **c** Effect of gap on surface roughness [37]

consumption. The result showed that increasing the pulse on-time results in a greater MRR, whereas the pulse-off time value of 6 μs yields the best results. During the process, surfactant helps to increase the plasma channel and it leads to the best output.

Sidhu [57] worked on the surface alteration of designed nontoxic β-Ti alloys and presents the optimum process parameter to obtain a biocompatible surface. The experiment was performed on EDM with different current values and pulse on

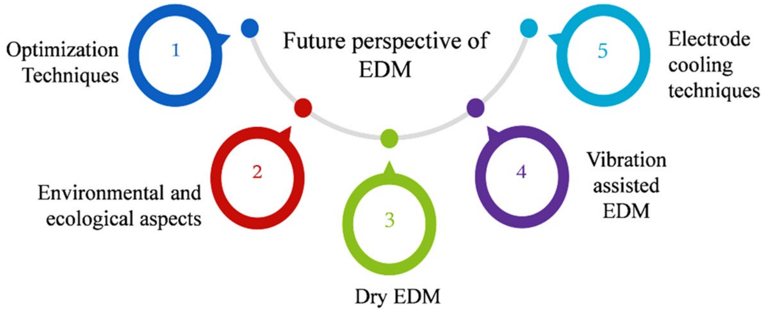


Fig. 11 Future research directions for the EDM

and pulse off with negative and positive polarities at a preset gap voltage of 140 V between electrodes. By using deionized water as a dielectric medium and a fine-grained graphite tool, the finished surface has been examined for the % hemolysis test. It was found that surface-modified after electro-discharge process reduces % hemolysis due to carbide/oxide surface formation. The formation of a rough porous surface at a high current (10A) improves cell anchoring with implants and stimulates the patient's post-surgery healing process.

Pramanik et al. [27] examined the impacts of varied machining parameters such as pulse on time, flushing pressure, and wire tension on machined surface morphology by using WEDM on Ti6Al4V alloy. Swiercz and Holubek [58] investigated the effects of discharge current and pulse time on the surface roughness and the average white layer thickness. The finding revealed that machined surface layer properties play a critical role in manufacturing component performance.

Future aspects

Titanium alloy is an expensive metal that is utilized mostly in aerospace and biomedical applications due to its unique characteristics. For those applications, titanium alloy parts must be defect-free, and these parts are generally made using standard machining techniques. Manufacturing sectors have become more concerned in recent years about environmental and ecological aspects of production, in addition to productivity and component quality. Dry EDM processing also gaining popularity in the research community. Other than quality and productivity, the reduction in power consumption leads to a reduction in energy waste and lower machining expenses has and which are environmentally friendly. Furthermore, advances in hybrid methods by combining numerous methods may overcome the drawbacks of different methods and the benefits of different methods are maximized to improve machining performance. High-frequency vibration has a notable effect on the MRR therefore vibration-assisted EDM develop in the future. The different optimization techniques and electrode cooling techniques may be implemented to lower the tool wear rate. The future study is to be focused on the development of a new powder that can be used in EDM. Figure 11 presents a future research direction for the EDM.

Conclusions

This research paper reviewed the types of EDM machines, machining process, process parameters, and their effect on the performance of titanium alloy. It is an attempt to study of work of various researchers in the area of EDM and titanium alloy. EDM is highly recommended for difficult-to-cut materials. EDM is a highly recommended industry for high material rates using different types and materials of tool electrodes, dielectric fluid, and machining parameters. The review also revealed that ultrasonic vibration has a significant influence on the performance of the EDM process. The surface integrity is better in an ultrasonic-assisted process than in conventional EDM. Titanium alloy is widely used for implant-bone replacement therefore surface qualities play a key and extremely important function in new bone production and future tissue growth. For better bio-adaptability, there is scope for research on electrical discharge machining in surface modification of titanium alloy. The performance enhancement EDM on titanium alloy, a comprehensive analysis of process parameters, cutting characteristics, and surface integrity need to investigate.

Abbreviations

EDM	Electric discharge machining
EBM	Electron beam machining
CNC	Computer numerical control
LBM	Laser beam machining
MRR	Material removal rate
TWR	Tool wear ratio
MIMO	Multiple-input multiple-output
WEDM	Wire-electrical discharge machining
ANN	Artificial neural network
SR	Surface roughness
ANOVA	Analysis of variance
USM	Ultrasonic machining
μ-USEDM	Micro-ultrasonic-assisted electric discharge machining
DOE	Design of experiments

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Not applicable.

Authors' contributions

The first draft of the manuscript was written by RR. DK and NA performed the conceptualization of the research idea, participated in the interpretation of the results, and reviewed the edited manuscript. All authors have made a substantial contribution to the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare that they have no competing interests.

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