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ORIGINAL ARTICLE

Electric discharge machining of titanium and its alloys: review

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Abstract

Electric discharge machining (EDM) is one of the leading edge machining processes successfully used to machine hard-to-cut materials in wide range of industrial applications. It is a non-conventional material removal process that can machine a complex shapes and geometries with high accuracy. The principle of the EDM technique is to use thermoelectric energy to erode conductive components by rapidly recurring sparks between the non-contacted electrode and workpiece. To improve EDM performance, the machine's operating parameters need to be optimized. Studies related to the EDM have shown that the appropriate selection of the process, material, and operating parameters had considerably improved the process performance. This paper made a comprehensive review about the research studies on the EDM of different grades of titanium and its alloys. This review presents the experimental and theoretical studies on EDM that aimed to improve the process performance, including material removal rate, surface quality, and tool wear rate, among others. This paper also examines evaluation models and techniques used to determine the EDM process conditions. Moreover, the paper discusses the recent developments in EDM and outlines the progression for future research.

Keywords EDM · Titanium · Machining · Process parameters

1 Introduction

Titanium and its alloys have high strength-to-density value and corrosion resistance characteristics. Due to these unique characteristics, titanium and its alloys are extensively used in a wide range of applications. However, titanium and its alloys are considered as hard-to-cut material using conventional manufacturing processes [1–3]. The superior properties of these hard-to-cut materials increase their applications, which further drive manufacturers to explore new machining processes with reasonable cost and precision.

Electric discharge machining (EDM) is one of the non-conventional machining processes successfully used to machine hard-to-cut materials [4–7]. This process has been used in modern industries to facilitate highly accurate machining, cut complex shape, and with better surface conditions [8–13]. One of the advantages of the EDM techniques is that the tool (electrode) and the workpiece do not touch each other; this leads to residual stress free material after machining [10, 14–16]. The basic principle of the EDM process is applied in many forms hence resulting into different process variants, including sinking EDM or die-sink EDM, wire EDM, micro-EDM, powder-mixed EDM, and dry EDM. Due to the wide varieties of EDM processes, it is suitable for both relatively large and micro-scale machining areas.

EDM is a manufacturing process whereby a desired shape is obtained by using electrical discharge (sparks). It is also known as a spark machining, spark eroding, die sinking, wire erosion. The process is based on the principle that the workpiece and the tool (electrode) not touching each other.

This study aims to capsulate the vast research in the field of the EDM technique of titanium and its alloys. This paper made a comprehensive review about the research work

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conducted on titanium and its alloys using all types of EDM processes. The paper starts with a brief introduction on titanium and its alloys and EDM techniques, and then it introduces the working principle of this machining method. The EDM process parameters and its performance measures are then discussed. This is followed by description of the different types of EDM processes and the research studies conducted. The conclusions and the trend of the reviewed bodies of research are subsequently drawn after the focus of the current publications is discussed. Future research directions are discussed in the end.

2 General view of the EDM method

2.1 EDM principle

The EDM manufacturing process was invented in the 1940s [10]. The principle of the EDM technique is to use thermoelectric energy to erode a workpiece by rapidly recurring electrical discharges (sparks) between the non-contacted electrode and workpiece [17–20]. The spark current (*Is*) flows between the electrode and the workpiece through the small distance between them, called as "gap" that filled with dielectric fluid. Flushing the dielectric fluid during the machining process carries away debris (removed solid particles) and restores the sparking condition in the gap. No cutting forces are used between the electrode and the workpiece as no contact exists between them. This condition eliminates vibration or stresses during machining. Moreover, mechanical residual stresses are also eliminated [21–23].

2.2 EDM process conditions and their effects on the performance parameters

EDM process drives by many parameters such as voltage, peak current, pulse on time, pulse off time, discharge gap, polarity, pulse wave form, flushing of the dielectric fluid, and workpiece rotation. The details of these parameters are described in the coming sections.

Discharge voltage (V) It is the average voltage in the gap between the electrode and workpiece during machining. *V* directly influences the regulation of the spark gap size and overcut [24–27]. Low *V* is recommended for highly electrical conductive materials. In contrast, the electrode and workpiece materials that have low electrical conductivity use a high *V*.

Peak current (Ip) It is the amount of power spent in discharge machining. The *Ip* has a direct influence on both material removal rates, electrode wear rates, and the machining accuracy [28–32].

Pulse on time (Ton) It is the time of the discharge duration. The amount of energy generated during the *Ton* effect directly the material removal rate (MRR) [33–36] which increases with longer *Ton* [37].

Pulse off time (Toff) It is the time period in which no discharge is applied. This time period follows each *Ton* to let the debris flushing away from the machining zone. The proper selection of the pulse off time ensures a stable machining [38–40].

Polarity (P) It is the positive or negative charge. One of the two charges for the electrode and the workpiece has the opposite charge polarity. Normally, electrode has positive charge polarity [41, 42].

Discharge gap (G) It is the distance between the tool and the workpiece. The proper *G* is normally between 0.01 and 0.1 mm and it decreases to a few microns in micro-EDM [43, 44].

Flushing It is one of the non-electrical parameters that refers to the flow speed of the fluid towered the machining area. Flushing of dielectric fluid reduces the temperature of machining area and cleans away the debris from it. Many studies have recently been conducted to explore oil-based synthetics to avoid harmful effects to the worker and the environment [45–47]. The dielectric type and the flushing method influence the MRR, electrode wear rate (EWR), and surface roughness (Ra) [48–51]. The dielectric flushing conditions can be improved with the workpiece and electrode rotation [52, 53]. This improvement of flushing caused by the electrode rotation achieves a better Ra and a higher MRR [54–56] and minimizes the density of the crack generation and the recast layer [50].

The effect of the EDM process conditions on the performance parameters cannot be easily explained because of the stochastic nature of its discharge mechanism [57]. Therefore, many studies related to the EDM process have explored the impact of the operating parameters on the performance measures [11, 34, 36, 58, 59].

2.3 Performance measure parameters

The performance of EDM process is measured by many factors, mainly MRR, EWR, and surface quality.

MRR: it is expressed by the volume of the removed material per unit time. The manufactures' goal is to improve the MRR techniques and method [60–64]. One of the limitations of EDM process is that it has low MRR compared to the other non-conventional machining processes. That is why it is very important to elevate the MRR of EDM process.

EWR is the erosion rate from the tool electrode. Similar to the MRR, the EWR can be calculated by the volume of the material removed from the electrode per unit time. The previous studies focus on reducing the EWR because the wear of the electrode affects the electrode profile and leads to a lower level of precision [59, 65, 66].

Surface quality is a measure of the quality of the machined surface conditions. The surface quality measurement includes surface roughness, heat affected zone, recast layer, and density of micro-cracks. Many research studies have been introduced to explore the utilization of the EDM process in surface treatment and report the surface effectiveness caused by the process Schumacher [67].

2.4 Types of EDM processes

2.4.1 Sinking EDM

In this process, the controlled electrical spark is repeated to replicate the shape of electrode into the workpiece. In this case, the electrode moves in vertical direction only. The process can also be applied by electrode movement in 3D to machine the workpiece. A combination of the two cutting systems could also be applied. The machining area of sinking EDM process has very high temperature (i.e., 8000 to 12,000 °C). In sinking EDM, copper and graphite are widely used as an electrode material. Normally, new electrode is used to execute the finish machining (cutting to final dimensions) due to the electrode wear that leads to change of geometries in rough machining stage. This process uses hydrocarbon dielectric fluid because of its positive effect on the Ra and EWR [68, 69]. Figure 1 shows a schematic diagram of the sinking EDM [70] elaborated with the components.

2.4.2 Wire extend EDM

In wire EDM, a metallic wire of small diameter follows a well-defined path to cut a workpiece. Discrete sparks between the wire and the workpiece cause eroding in the machining area. Since, it is a type of EDM process; therefore, the wire and the workpiece do not have any direct contact during machining. The wire used in this process is usually with a relatively small diameter ranging from 0.1 to 0.3 mm. It is normally made up of copper, brass, or coated steel materials. Deionize water is a common dielectric fluid used in this process. The wire EDM process has a wide range of applications, such as in the die making, medicine, electronics, and automotive industries [25]. Figure 2 shows a schematic diagram of the wire EDM [71].

2.4.3 Micro-extend EDM

In the micro-EDM the principles of the sinking EDM and wire EDM in micro-scale level are similar. In this process, the required extend *V* and *Is* are several times lesser than those used in macro-level EDM processes. This process can produce successfully hole or shaft diameters of 5 μm [21].

2.4.4 Powder-mixed extend EDM

In this process, a powder of a suitable material is conglomerate with the dielectric fluid. The presence of this powder altered the process mechanism completely from the conventional EDM process [72]. The powder particles fill the gap between the electrode and the workpiece. When a *V* is applied during the machining, this particle relocation forces the electrode and the workpiece to move away from each other at a small distance to replace the gap area reduction filled by the powder particles. The presence of the powder particles arranged between the electrode and the workpiece leads to earlier explosion and faster sparking, which cause a higher erosion rate, hence more MRR.

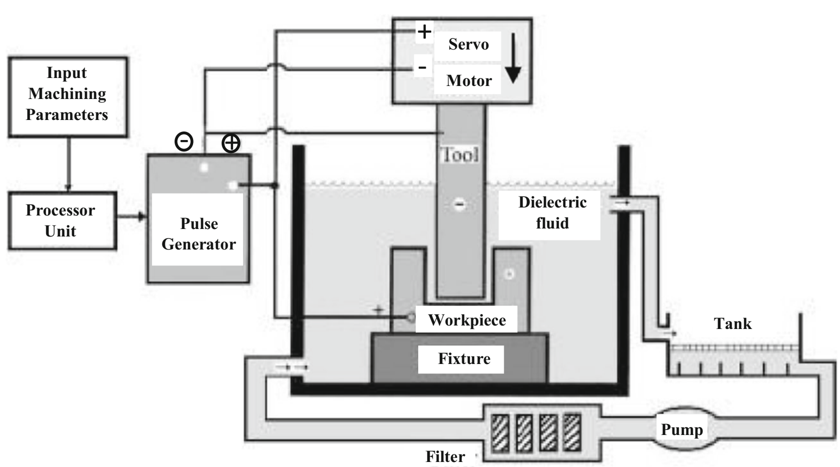

Fig. 1 Schematic diagram of sinking EDM [70]

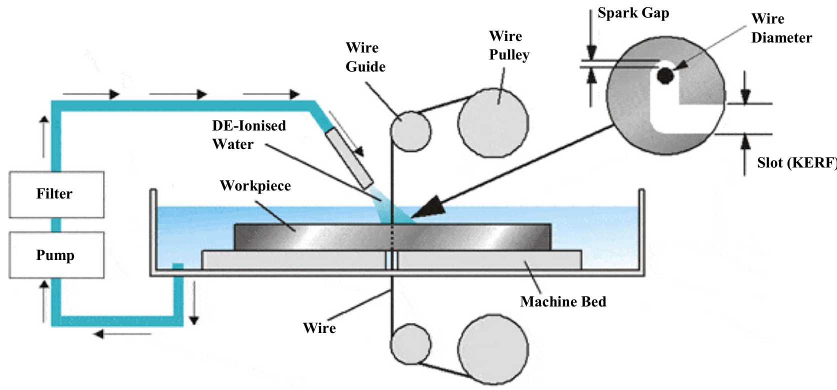

Fig. 2 Schematic diagram of wire EDM [71]

2.4.5 Dry extend EDM

The dry EDM uses dielectric high-pressured gas instead of dielectric liquid used in the other EDM processes [5, 73–76]. The dry EDM process positively influences the extend MRR and reduced the electrode wear ratio [74, 75, 77].

3 Titanium and its alloys

Titanium is a low-density element that can be invigorated greatly by alloying and deformation processing [78]. Titanium and its alloys have a combination of unique properties such as high strength, stiffness, superb toughness biocompatibility, low density, and splendid corrosion resistance at very low to elevated temperatures. Such outstanding properties permit weight reduction in aerospace structures and other high-performance applications [79]. Titanium and its alloys have attractive high strength-to-density characteristics and exceptional corrosion resistance derived from its protective oxide film. They are extensively used in several fields such as biomedical and aerospace industries like aircraft engines and airframes, missiles, spacecraft, chemical and petrochemical production, and many other areas [79].

Properties of widely and recent used of different grades of titanium and its alloys and EDM process considered for each grade are summarized in Table 1.

Table 1 Details of EDM process used titanium and its alloys

Different grades	Corresponding machining operations
Ti–6Al–4V	Die Sinking EDM: [30, 53, 80–100] wire EDM: [83, 101–108] micro-EDM: [109, 110] powder-mixed EDM: [111–114]
Gamma titanium aluminide (γ-TiAl) alloys	Die sinking EDM: [115–117] wire EDM: [118–120] micro-EDM: [121] powder-mixed EDM: [122] dry EDM: [123]
Titanium alloy TC11	Micro-EDM: [120]
Ti-5Al-2.5Sn titanium alloy	Die sinking EDM: [94, 114]
Titanium alloy TC4	Die sinking EDM: [124, 125]
Alpha-TiAl (Ti–46.5Al–4(Cr, Nb, Ta, B))	Wire EDM: [108]
Titanium alloy Ti–46Al–2Cr	Wire EDM: [112]
Ti-6Al-2Sn-4Zr-6Mo aerospace alloy	Wire EDM: [126]
Ti alloy, ASTM grade II	Die sinking EDM: [94]
Other grades of titanium and its alloys	Die sinking EDM: [80, 102, 104, 118, 119, 127–136] wire EDM: [113, 137] micro-EDM: [138] dry EDM: [114]

4 Relevant literature on EDM

In this section, the studies dealing with titanium and its alloys using EDM processes are reviewed based on the following classification scheme:

Type of EDM process: The relevant studies are classified according to the EDM process used to machine the titanium and its alloys' workpiece as follows:

D-S Die sinking EDM
W Wire EDM
μ Micro-EDM
P-M Powder-mixed EDM
D Dry EDM

Objective function: The following objective functions are reported in the current relevant literature:

Objective 1: Performance measures in EDM of titanium and its alloys
Objective 2: Effect of EDM process on the surface integrity
Objective 3: Modeling and simulation of EDM process
Objective 4: Electrode material and shape in the EDM of titanium and its alloys
Objective 5: Combined and hybrid processes of titanium and its alloys
Objective 6: Dielectric fluid research
Objective 7: Other bodies of research on titanium and its alloys using EDM

Using this classification scheme, Table 2 chronologically lists the studies for titanium and its alloys machined using different EDM processes.

4.1 Performance measures in EDM of titanium

Several bodies of research have been conducted to study the effect of the working parameters on the performance parameters during the EDM process of the titanium and its alloys. Many methods have been introduced to improve these parameters. Accordingly, Khan et al. [111] developed ANN model to predict Ra. The result showed that the ANN model can predict the Ra effectively. The authors reported that the Ra increases with pulse on time. Low peak current as well as low discharge energy level results in smaller craters and micro-cracks. On the other hand, high discharge energy produces higher degree of craters as well as greater degree of cracks, generating a rougher surface. Based on the SEM images in Fig. 5, the sizes of the craters increase with the discharge energy level. The fine microstructure of the machined surface is gained with low discharge energy.

Furthermore, Manjaiah [139] proposed modified Taguchi method to optimize process parameters, namely, *Ton*, *Toff*, servo voltage (Vs), flushing pressure, and wire speed, to simultaneously optimize MRR and Ra of TiNI machined on WEDM. He also studied the surface morphology, recast layer, hardness, and microstructure of machined surface. Ntasi [152] found the optimal values of parameters that achieved maximum MRR, minimum EWR, and minimum hole taper in hole sinking electrical discharge micromachining. The study developed an integrated model of single hidden layer back propagation neural network. The study considered *V* and capacitance of capacitor as process parameters and the MRR, EWR, and hole taper as performance parameters. The authors reported that the proposed integration model was able to predict and optimize the process performance with plausible accuracy.

Klocke [115] studied the MRR and volumetric relative wear (VRW) and surface integrity of two grades of γ-TiAl namely, 45XD and GE 48-2-2 machined on sinking EDM. It was found that the machinability of the two grades mentioned above has dissimilar machinability using EDM processes compared to common titanium alloys. The authors reported that the two grades had almost the same level of MRR compared to nickel alloys and titanium-based alloys. Xiangzhi [140] studied dielectrics with different conductivities in EDM of titanium alloy to explore the influence of conductivity on MRR, EWR, and Ra. In the initial stage, increasing conductivity resulted in increasing the MRR with the wider G. When there is more energy wasted in the G and electrolysis, MRR begins to decrease. Both EWR and Ra increased with the growth of conductivity. When the conductivity of water is 69 μs/cm, the best machining effect in titanium alloy EDM was achieved. Gu [84] investigated the feasibility of bundled electrode to machine Ti6Al4V on EDM process. The study compared experimentally the bundled electrode with solid electrode. It was found that the bundled electrode achieved high performance of the EDM process, because the bundled electrode used multi-hole inner flushing, and these flushing holes efficiently remove the debris from the machining area.

Rangajanardhaa [86] studied the effect of operating parameters including the Ip and V on the Ra to find the optimal parameters that achieve the lowest Ra for Ti6Al4V, HE15, 15CDV6, and M-250 on EDM. The study developed multi-perceptron neural network models. Genetic algorithm (GA) was utilized to optimize the weighting factors of the network. The models were evaluated experimentally. It was found that the Ra increased tremendously as the Ip increased.

It has been reported also that the type of material had the highest influence on all performance measures. Furthermore, Sarkar [119] studied the WEDM of γ-titanium aluminide. The study developed a feed forward back-propagation neural network. Cutting speed, Ra, and

Table 2 List of the studies for titanium and its alloys machined by different EDM process

		EDM process					Objective function						
No.	Ref.	D-S EDM	W EDM	µ EDM	P-M EDM	D EDM	1	2	3	4	5	6	7
1	[30]	x									√		
2	[53]	x					√						
3	[111]	x					√		√				
4	[139]		x				√	√	√				
5	[111]	x					√	√					
6	[140]	x					√					√	
7	[84]	x					√		√	√			
8	[86]	x					√		√		√		
9	[119]		x				√		√				
10	[103]		x				√						
11	[105]		x				√						
12	[94]	x					√						
13	[96]	x					√						
14	[106]		x				√						
15	[80]	x						√					
16	[127]			x			√	√				√	
17	[126]		x					√					
18	[85]	x						√					
19	[101]		x					√					
20	[138]			x			√	√					
21	[102]		x					√					
22	[108]		x				√						
23	[117]	x					√						
24	[104]		x					√					
25	[98]	x						√					
26	[128]	x						√					
27	[129]	x					√						
28	[118]		x						√				
29	[113]		x						√				
30	[120]		x						√				
31	[125]	x							√				
32	[88]	x								√			
33	[92]	x					√			√			
34	[97]	x					√			√			
35	[99]	x								√			
36	[130]	x								√		√	
37	[131]	x					√			√			
38	[141]	x					√		√				
39	[142]		x								√		
40	[89]	x									√		
41	[143]				x		√	√				√	
42	[122]				x		√					√	
43	[114]						√					√	
44	[121]			x				√	√			√	
45	[132]				x								√
46	[133]	x					√					√	
47	[134]				x							√	
48	[90]	x										√	

Table 2 (continued)

		EDM process				Objective function					
49	[124]	x				√				√	
50	[135]				x	√				√	
51	[95]	x				√				√	
52	[144]	x				√				√	
53	[145]	x				√				√	
54	[146]	x				√				√	
55	[83]	x	x								√
56	[87]	x									√
57	[147]	x									√
58	[116]	x									√
59	[112]		x								√
60	[91]	x									√
61	[93]	x									√
62	[148]	x									√
63	[149]	x									√
64	[150]	x									√
65	[151]	x									√
66	[100]	x									√
67	[110]			x		√					
68	[81]	x				√		√			
69	[82]	x							√		
70	[107]		x			√					
71	[109]			x		√		√			
72	[137]		x								
73	[151]	x					√				
74	[123]					√					

wire offset were considered as performance measures. The input parameters to the proposed model were *Ton*, *Toff*, *Ip*, wire tension, dielectric flow rate, and Vs. Also, Soni [53] presented an experimental investigation of the machining features of titanium alloy by means of EDM. The effects of *Is* and *w* on the MRR, EWR, and Ra were studied, and the results were compared with stationary electrodes. The study developed a mathematical model for the process. It was found that rotating the electrode improves the MRR. However, Ra was high. The EWR was increased with increasing electrode rotation speed (*w*). Furthermore, Nourbakhsh [103] conducted an experimental investigation on wire EDM of titanium alloy. The effects of working parameters including pulse width, Vs, *Is*, and wire tension on performance parameters including cutting speed, wire rupture, and surface integrity were investigated. It was found that the cutting speed was increased with *Ip* and *Toff*. Regarding the Ra, it was found to increase with pulse width and decrease with *Toff*. It was also reported that the *V*, injection pressure, wire feed rate, and wire tension had non-significant effect on the cutting speed. Also, Alias [105] explored the effect of feed rate on the performance of WEDM of titanium Ti-Al-4V. The effects of working parameters on kerf width, MRR, and Ra were studied. Figure 3 shows the relationship between feed rate and MRR.

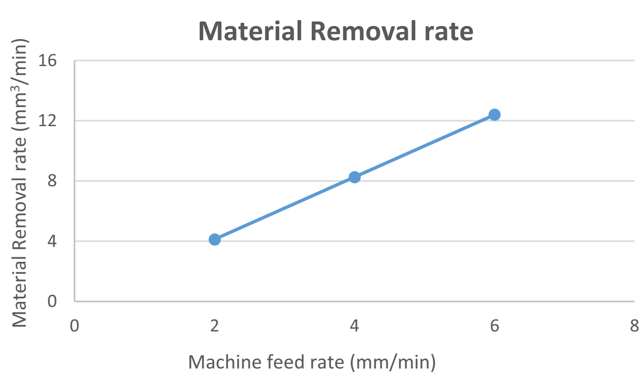

Fig. 3 Result on MRR at different machine rates [105]

Kumar [94] proposed a hybrid Taguchi-artificial neural network technique to predict Ra of titanium alloys during EDM. It was found that the *Is* and *Ton* significantly affected the performance characteristics of EDM of titanium alloys. Furthermore, high discharge energy caused surface flaws such as cracks, craters, thick recast layer, micro-pores, pin holes, residual stresses, and debris. Santos [96] studied the effect of working parameters including *Ip*, *P*, *Ton*, and duty time on MRR and surface integrity of Ti-6Al-4V in EDM with graphite electrodes. It was noticed that the positive *P* on the electrode led to lower Ra and MRR. Tsukahara [153] investigated the performance of wire EDM parameters on machining characteristic including MRR, Ra, and kerf width of titanium alloy. The study used Taguchi method to design the experimental matrix and analysis of variance to analyze the data. The study shows that the Vs contributes the most significant factor for MRR, while *Ton* contributes the most significant factor for Ra and kerf width. Furthermore, high-quality surface was achieved with low *Is* with long *Ton* time. Kumar [106] combined Taguchi and grey relational analysis method to find optimal working parameters of wire EDM process for machining Ti-6AL-4V. The study considered *V*, *Ton*, *Toff*, and wire feed as working parameters and the MRR and Ra as performance measures. The main researches in optimizing process parameters of EDM machining are summarized in Table 3.

4.2 Effect of EDM process on the surface integrity

Many studies focused on the effect of machining using different processes on surface integrity of titanium and its alloys while machined by different processes of EDM. For example, Mower [80] presented an experimental study to measure the fatigue strength of Ti–6Al–4V machined by EDM process. The authors reported that the reduction of fatigue strength depended on recast layers. The study also demonstrated post-processing with either electrochemical polishing or bead blasting to remove the deleterious effect of EDM process.

Figure 4 shows an example of EDM-induced damage at fatigue-crack initiation sites. Also, Chen et al. [127] studied the surface modification of titanium due to machining by micro-EDM at various working parameters. They have reported that the suitable concentration of titanium powder into the dielectric fluid raised the wettability on the surfaces of titanium during MC-EDM modifications in addition to its ability to avert the formation of surface cracks and micro-cracks. Also, Chen et al. [127] studied the surface modification of titanium machined in micro-EDM at various working parameters. The authors reported that the suitable concentration of titanium powder into the dielectric fluid raised the wettability on the surfaces of titanium during MC-EDM modifications in addition to its ability to avert the formation of surface cracks and micro-cracks. Figure 5 presents SEM micrographs of modified Ti at different working parameters in deionized water mixed with Ti powder dielectric solvent. Soo [126] studied the fatigue behavior of Ti-6Al-2Sn-4Zr-6Mo on WEDM process. The results were revealed that there was no statistically significant variation in fatigue performance between WEDM finishing and flank milling of the specimens when using minimum damage EDM generator technology and optimized trim-pass strategies. Figure 6 shows the S-N curves for the WEDM and milled fatigue specimens. Fractography data showed that for specimens machined using both processes, crack initiation was predominantly within the first 40–50 μm from the surface despite the absence of any major machining-related damage. Harcuba et al. [85] studied the properties of Ti–6Al–4V alloy machined by EDM. The study evaluated the tensile tests and Ra for different *Ip* of the EDM process. They have reported that the treatment due to EDM process is promising surface modification to orthopedic implants. Figure 7 shows the SEM image of Ti-6Al-4V surface after EDM treatment.

Klocke [101] compared the effect of the grinding process and WEDM process on the fatigue strength and surface integrity of machined Ti6Al4V material. The ground specimen showed a higher fatigue life, while the specimen machined by EDM showed higher fatigue strength.

Ramkumar et al. [138] presented an experimental study of the plasma characteristics in the micro-EDM process using optical spectroscopy. They have studied the effect of process parameters including *V*, *Ip*, *G*, and electrode size on the plasma characteristics. The study revealed that the average plasma temperature and electron density were 6170 K and 3.5 × 10EP-18 cm^3, respectively. The electrode size and *G* play a major role in determining the plasma characteristics in micro-EDM. Also, the plasma temperature and electron density were higher with smaller electrode size and larger *G*. Aspinwall et al. [102] investigated *Ra* and integrity of Ti–6Al–4V and Inconel 718 machined using WEDM with minimum damage generator technology. They have reported that the average recast thickness was less than 11 mm.

Lee et al. [108] investigated the machined surface modification of γ-TiAl and Ti–6Al–4V during wire EDM using deionized water dielectric with nickel and copper wires. It was found that wire EDM of Ti–6Al–4V and γ-TiAl with copper and nickel wires produced uneven recast layers with a wide range of thickness. Similarly, Aspinwall et al. [117] conducted experimental study to investigate the influence of EDM parameters on the hardness of the white layer. Kuriakose and Shunmugam [104] studied the surface characteristics of Ti6Al4V machined using WEDM. The study proposed new approach to find the effect of process parameters on the surface features. It was found that the coated wires were better than the uncoated wires in terms of obtaining uniform surface characteristics. Furthermore, the time between two pulses was the subtlest parameter that affects the creation of layer

Table 3 Summary of recent researches in optimizing machining process parameters of titanium and it alloys

No.	Publication	Process	Working parameters	Performance parameters	Remark (note)
1	[143]	PMEDM	Powder concentration	MRR, Ra, EWR	The MRR was extremely improved by mixing B4C powder into the dielectric fluid. The TWR increased with increasing the concentration of B4C powder. The Ra improved by adding B4C powder. Furthermore, adhering phenomenon was observed on the machined surface at high concentration of B4C powder, and the high concentration of the powder achieved good surface finish and less cracks and craters.
2	[111]	EDM	*Ip Ton*, *Toff*, and Vs	Ra	The Ra increases with *Ton*. Low *Ip* as well as low discharge energy level results in smaller craters and micro-cracks.
3	[139]	W EDM	*Ton*, *Toff*, Vs, flushing pressure, and wire speed	MRR and RA	This study proposed modified Taguchi method to optimize process parameters.
4	[81]	EDM	*V*, capacitance of capacitor	MRR, TWR, and hole taper	The study developed an integration model and proved that the proposed model was capable to predict process performance.
5	[115]	EDM	Duty factor (τ), *Is*, open-circuit voltage	MRR and volumetric relative wear and surface integrity	The paper studied the EDM of two grades of γ-TiAl and compared their machinability.
6	[122]	PMEDM	The *Is*, *Ton*, powder size, and powder concentration	Ra and topography, MRR, and corrosion resistance	The aluminum powder produced the best surface finish and surface topography, followed by SiC, Gr, Cr, and Fe in sequence. Many elements such as titanium, aluminum, carbon, oxygen, and copper were present in all machined surfaces.
7	[138]	micro-EDM	*V*, *Is*, *G*, and electrode size	Plasma characteristics	The electrode size and *G* play a major role in determining the plasma characteristics in micro-EDM. Also, the plasma temperature and electron density were higher with smaller electrode size and larger *G*.
8	[86]	EDM	The *Ip* and *V*	RA	The Ra was increased tremendously as the *Ip* increased.
9	[133]	EDM	Dielectric type, *Ip*, and *Ton*	MRR, EWR, Ra	The MRR and EWR were increased with adding urea into the dielectric. The machined surface wear resistance was improved due to migrated of nitrogen elements to the workpiece surface which made TiN hard layer.
10	[110]	Micro EDM	*P*, *Is*, Ton, and *w*	MRR, EWR, Ra	Proposed modified EDM by using a rotating disk as the electrode. The MRR has great improvement in the modified EDM process.
11	[53]	EDM	*Is* and w	MRR, EWR, Ra	The paper developed a mathematical model of the EDM process. The rotating of the electrode was improved the MRR. However, Ra was high. The EWR was increased with increasing the speed.
12	[124]	EDM	Dielectric fluid	MRR, relative EWR, and RA	The compound dielectric fluid was achieved the higher MRR, a lower relative EWR than that in kerosene. Moreover better SF and fewer micro-cracks than that in distilled water.
13	[92]	EDM	Different electrode materials, *Is*, *Ton*, *Toff*	MRR, EWR, and overcut	The appropriate electrode material for machining titanium alloys was copper-infused graphite. Also, the MRR was mainly influenced by *Ton* and *Is*, whereas *Toff* had least effect on MRR. Furthermore, EWR was mainly effected by pulse on time and pulse off time, whereas *Is* had least effect on EWR.
14	[135]		*Is*	The MRR, RA, and TWR	The MRR was higher, and TWR and Ra were lower for machining titanium alloy in EDM with additives added in dielectric fluid compared to dielectric fluid without additives. Furthermore, the formed recast layer when adding additives to the dielectric fluid was smaller than the formed layer in dielectric medium without additives added.
15	[95]	EDM	*Ton*, *Ton*, and *Ip*	MRR and RA	The addition of multi-walled carbon nanotubes in dielectric leads to substantial improvement in MRR and Ra.
16	[106]	wire EDM	*Vp*, *Ton*, *Toff*, and Wire Fee	MRR and RA	The study combined Taguchi and grey relational analysis method to find optimal working parameters of wire EDM process for machining Ti-6AL-4V.
17	[144]	EDM	Dielectric viscosity	MRR, relative EWR	The MRR was increased when raised the viscosity but when it is excessive, MRR was reduced. EWR and RA decrease as the viscosity rises. Finally, raised the viscosity, decreased the

Table 3 (continued)

No.	Publication	Process	Working parameters	Performance parameters	Remark (note)
					thermal conductivity of dielectric and lower cooling speed which led to produce less micro-cracks
18	[96]	EDM	*Is*, *P*, *Toff*, and duty time	MRR and surface integrity	The positive *P* on the electrode led to lower RA and MRR.
19	[97]	EDM	*Ip* Ton and flushing pressure	MRR, EWR, and RA	The process with copper electrode led to higher MRR and lower EWR compared to the processes with brass and aluminum electrodes. Also, brass and copper electrodes had better surface finish compared to aluminum electrode. The study was reported that electrode material for machining of Ti6Al4V alloy in EDM process was in the order of copper, brass, and aluminum
20	[107]	Wire EDM	*Ton*, *Toff*, Vs, and *Is*	MRR, RA, and kerf width	The Vs contributes the most significant factor for MRR, while *Ton* contributes the most significant factor for Ra and kerf width. Furthermore, High-quality surface was achieved with low *Is* with long *Ton* time

consisting of mixture of oxides. Formation of oxides was lower with lower value of time between two pulses.

Thesiya et al. [98] studied the heat affected zone and recast layer of Ti-6Al-4V alloy machined by the EDM process. The study considered *Ip*, Vs, *Ton*, and *Toff* parameters. It was found that the recast layer formation was depended on types of material, machining polarity, and to some extent both *V* and *Ip*. Machining titanium alloy with copper electrode under low *V* and *Ip* led to higher Ra and less recast layer and vice versa for graphite electrode. Tsukahara et al. [128] used the scanning electrode to study surface modification of titanium during the finishing process of EDM. The study investigated the effect of working parameters including electrode thickness, scanning speed, and scanning pass on the surface properties. They have reported that the scanning electrode method proved to be effective for efficient surface modification of titanium. Yaman and Cogun [136] studied the surface modification of titanium after EDM process. The EDM finishing process was examined to study the formed titanium carbide layer on the machined surface. It was found that the relatively short discharge duration with low *Is* range under the electrode negative *P* led to formation of titanium carbide layer with less crack surface. Many other improvements in machined surface such as hardness, tribological properties, and corrosion resistance were also obtained. Tsukahara et al. [129] described the tribological properties of the carbonization layer of titanium using EDM process. A TiC layer with excellent tribological properties, low friction coefficient, minimal fluctuation, and wear of mating material ball was obtained.

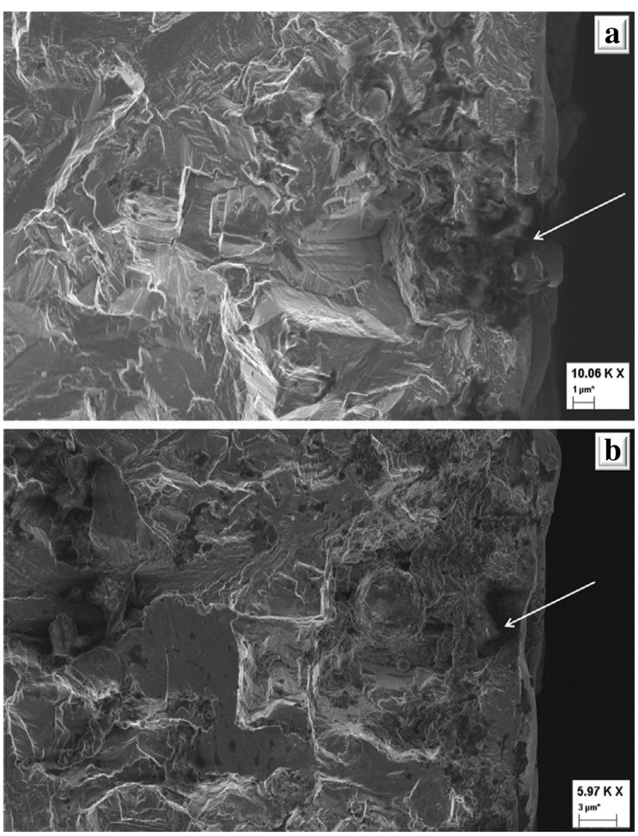

Fig. 4 Examples of intrinsic defects within the Ti–6Al–4V material studied. Inclusion (**a**) and void (**b**) [80]

4.3 Modeling and simulation of EDM process

Many modeling and simulation techniques were presented to find the optimal conditions for EDM process. Amran et al. [107] proposed a prediction of MRR in EDM TC11 workpiece based on the construction method of gray GM(1,N) model and BP neural network model (GNNM). The study provided a guideline to choose the process parameters for EDM TC11 process. Sarkar et al. [118] constructed a second-order mathematical model for Ra, dimensional shift, and cutting speed using RSM. It was found that the Ra was increased with cutting speed. Figure 8 shows the maximized cutting speed vs. Ra. They have reported that the developed technology table can be acted as a guideline for optimum

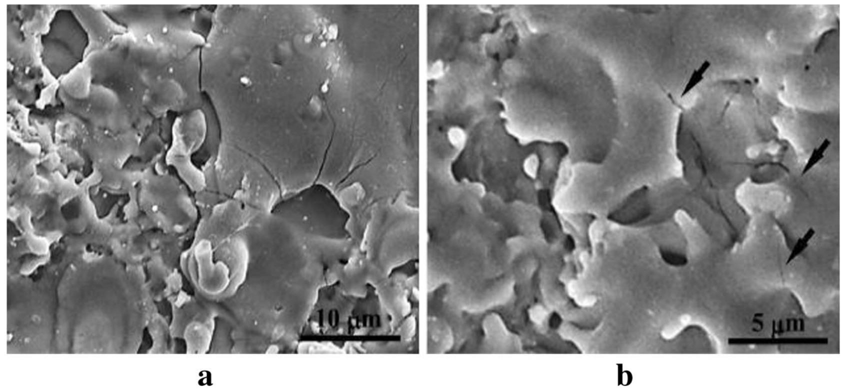

Fig. 5 The SEM micrographs of modified Ti at different working parameters in deionized water mixed with a concentration of 3 g/l Ti powder dielectric solvent. **a** 0.5 A for 10 μs and **b** 0.1 A for 10 μs [127]

machining of γ-TiAl alloy. Kuriakose and Shunmugam [113] presented a multiple regression model to study the relationship between process and response parameters. A multi-objective optimization approach based on a non-dominated sorting genetic algorithm was used to optimize wire EDM process for titanium alloy.

Sarkar et al. [120] presented an experimental investigation on single pass cutting of WEDM of γ-titanium alloy. Additive model was used in this study to model the process for response parameters prediction and to study the effect of operation parameters on the process parameters. It was found that the Ra and dimensional deviation were independent of the *Toff*. The study used constrained optimization and Pareto optimization algorithm to optimize the process under single and multi-constraint conditions. They have shown that propose approach was exceptionally suitable for increasing the productivity while keeping surface finish and geometrical accuracy within preferred limit. Liu et al. [125] developed a 3D thermodynamics model of single pulse discharge material removal using ANSYS software to simulate the tool wear in EDM small holes through titanium alloy. They have carried out experiments on small hole EDM machining through TC4 and compared simulation and experiment results. It was found that the simulation model accurately predicted the relative wear of electrode and the material removal volumes.

4.4 Electrode material and shape for the EDM of titanium and its alloys

Several concerns related to the influence of electrode materials on the EDM performance are studied by many researchers. Hascalık and Caydas [88] studied the effect of EDM operating factors on the surface integrity of Ti–6Al–4V. The study considered three electrode materials namely, graphite, electrolytic copper, and aluminum and *Is* and *Ton* as working parameters. It was found that the MRR, Ra, EWR, and average white layer thickness were increased with increasing *Is* density and *Ton*. Though, excessively long *Ton* such as 200 μs decreased MRR and Ra. The study reported that the graphite electrode was beneficial for MRR, EWR, and surface crack density but comparatively inferior surface quality. Figures 9 and 10 show the cross-sectional view of white layer with copper and graphite

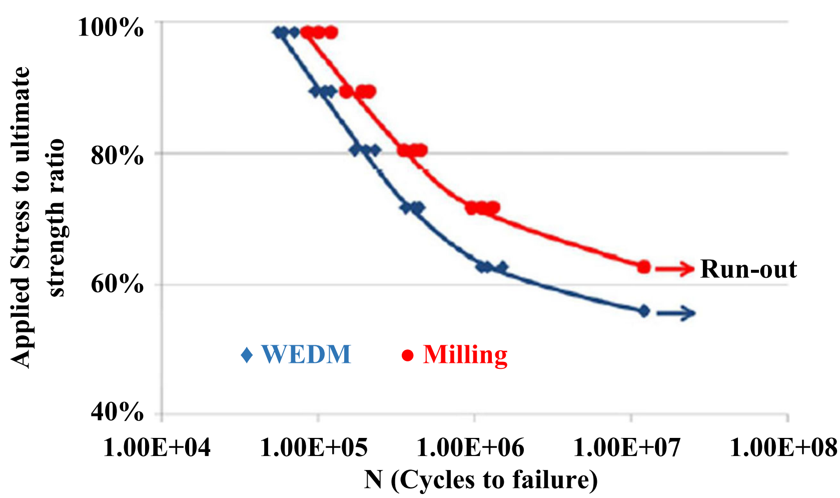

Fig. 6 S-N fatigue curves for Ti6246 specimens [126]

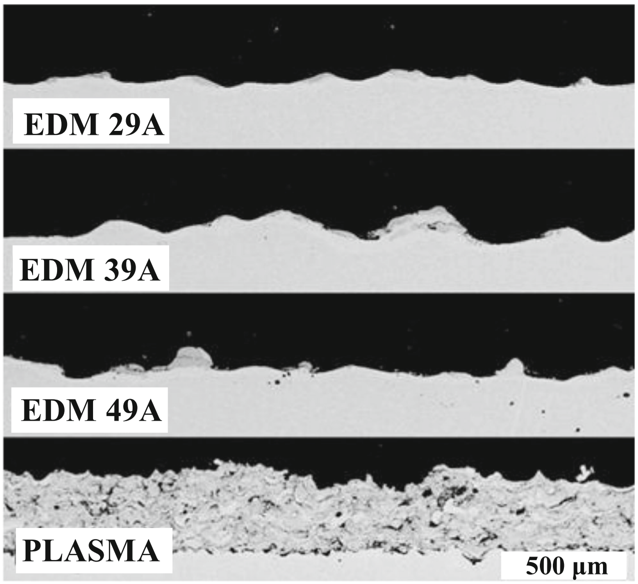

Fig. 7 SEM (backscattered electrons) images of surface layer and surface profile of Ti-6Al-4V after EDM with peak currents of 29, 39, and 49 A and also after plasma-spraying with TiO_2 [85]

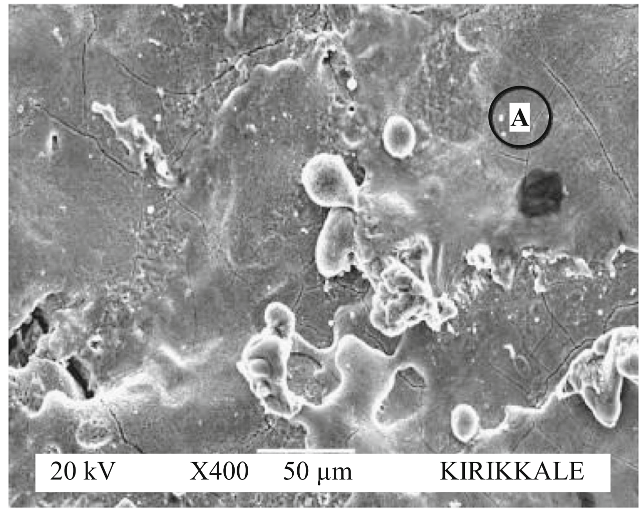

Fig. 9 A typical surface after EDM (IP 12 A; Ton 100 µs; electrode material: copper) [88]

electrodes, respectively. Sivakumar and Gandhinathan [92] studied the influence of electrode materials in machining of titanium alloys in EDM. The study explored various electrode materials, namely electrolytic copper, beryllium copper, tungsten copper, graphite, aluminum, steel (EN24), and copper-infused graphite. The study utilized the Taguchi method to find the effect of working parameters including *Is*, *Ton*, and *Toff* on MRR, EWR, and overcut. It was found that the appropriate electrode material for machining titanium alloys was copper-infused graphite. Moreover, the MRR was mainly influenced by *Toff* and *Is*, whereas *Toff* had least effect on MRR. Furthermore, overcut is mainly influenced by *Is* and *Ton*, whereas *Toff* had a minor influence on over cut. Kuttuboina et al. [97] studied the effect of working parameters including *Ip*, *Ton*, and flushing pressure on EDM of Ti–6Al–4V with three different tool electrode materials, namely copper, brass, and aluminum. The study considered the MRR, EWR, and Ra as response parameters. The results showed that the process with copper electrode led to higher MRR and lower EWR compared to the processes with brass and aluminum electrodes. Also, brass and copper electrodes had better surface finish compared to aluminum electrode. The study was reported that tool material for machining of Ti6Al4V alloy in EDM process was in the order of copper, brass, and aluminum. Uthirapathi [99] used six electrode materials namely, copper, brass, tungsten carbide, aluminum, austenitic stainless steel 304L, and austenitic stainless steel 316 to achieve more efficient MRR coupled with reduction in ETW. The study

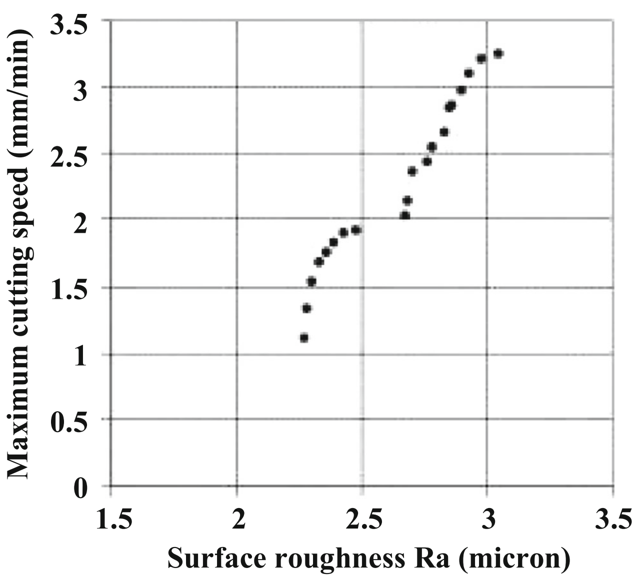

Fig. 8 Maximized cutting speed vs. surface roughness [118]

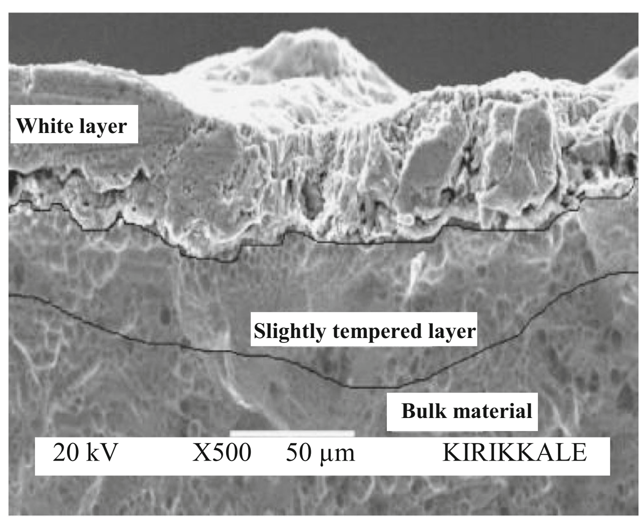

Fig. 10 Cross-sectional view of white layer (IP 6 A; Ton 100 µs; electrode material: graphite) [88]

compared the machining performance of Ti6Al4V with the electrode materials mentioned above in EDM and rotary EDM.

Obara et al. [130] studied the machining of titanium workpiece in EDM process using copper and titanium in two dielectric fluid mediums (namely, oil and water). It was found that the EDM of titanium that used the copper tool electrode in the water is more stable than that in the oil and had a low electrode wear ratio. Also, the EDM of titanium that used the titanium tool electrode in water had a EWR reduction by 10%, and the authors recommended using these conditions in machining the medical instruments. Zain et al. [131] studied the influence of electrode profiles on MRR and Ra of titanium. They have considered the following parameters; *Is*, *Ton*, and *Toff* as working parameters. The authors have reported the influence of electrode profile on the response parameters.

4.5 Combined and hybrid processes of titanium and its alloys

Many studied combined two or more methods to ameliorate the performance of EDM process. Gao et al. [141] combined the EDM technique, acid etching, and shot peening to form a superimposed topography that may improve the surface for osteoblast proliferation. The study was intended to utilize the proposed combination of modification to augment mechanical properties of the machined surface of Ti–6Al–4V alloy. It was found that the surface layers on the Ti–6Al–4V alloy surface created during EDM could be removed by chemical etching using strong Kroll etchant. Also, poor fatigue performance after EDM could be significantly improved using shot peening. The surface treatment due to consequent use of EDM and acid etching led to a superimposed surface topography. Proliferation of osteoblast-like cells was enhanced by the amalgamation of EDM, acid etching, and with or without shot peening.

Wansheng et al. [142] developed four-axis EDM to combine ultrasonic and micro-EDM. They have studied the effect of ultrasonic vibration on the EDM process. The experimental study showed that the holes of 0.2 mm diameter and a depth to diameter ratio of > 15 could be drilled steadily using the proposed combination. Wang et al. [89] proposed a merger of micro-EDM and micro-ultrasonic vibration lapping processes to machine micro-holes (less than 100 μm diameters) with high precision and aspect ratios. The authors reported that the roundness of the micro-holes was clearly improved while using either circular or stepped tools. Furthermore, Lin et al. [30] proposed an integration of EDM process with ultrasonic machining (USM) to improve the machining efficiency. The study investigated the machining characteristics of titanium alloy (Ti-6Al-4V). The influence of process parameters including dielectric type, abrasive size, concentration of abrasive in the dielectric fluid, discharge *Ip*, and *Ton* on MRR, EWR, REWR (Relative EWR), Ra, and recast layer thickness was investigated. It has been observed that the integration of EDM/USM process increased the MRR and decreased the thickness of the recast layer. This integration was very helpful in reducing the abnormal discharge and improving the discharge efficiency.

4.6 Effect of dielectric fluid on EDM performance

Dielectric fluids were focused by many studies in terms of performance improvement and to reduce its side effect on the process environment. Kolli and Kumar [143] introduced an experimental approach to investigate the effect of the boron carbide B4C powder mixed into dielectric fluid on MRR, EWR, and Ra. The MRR was extremely improved by mixing B4C powder into the dielectric fluid, and the optimum value of MRR was obtained at a powder concentration of 15 g/l. Regarding the EWR, it was found that the EWR increased with upsurge in the concentration of B4C powder and the lowest EWR was achieved at 1 g/l. The authors also reported that the Ra improved by adding B4C powder and the optimum Ra was achieved at 15 g/l. Furthermore, adhering phenomenon was observed on the machined surface at a high concentration of B4C powder, and the high concentration of the powder achieved good surface finish with no cracks and craters.

Jabbaripour et al. [122] studied the effect of powder mixed with dielectric material on the machining of γ-TiAl using powder-mixed EDM. They have studied the effect of many powders such as aluminum, chrome, silicon carbide, graphite, and iron on the performance parameters including Ra and topography, MRR, electrochemical corrosion resistance of machined samples, and the machined surfaces. The study revealed that the aluminum powder is the most suitable type of powder. The study then used the aluminum powder to compare the effect of process parameters including *Is*, *Ton*, powder size, and powder concentration on the performance of EDM and powder-mixed EDM. It was found that the aluminum powder produced the best surface finish and surface topography, followed by SiC, Gr, Cr, and Fe in sequence. At specific process parameters, aluminum powder in powder-mixed EDM process improved the Ra of TiAl machined surface with about 32% comparing with EDM process. It has been reported that the optimum value of particle concentration that decreased Ra machined surface was as follows: For Al, Gr, and SiC powders, it was 2 g/l, and for the Cr and Fe powders, it was 4 g/l. Aluminum particles with the size of 2 μm improved MRR about 54% comparing with EDM case. Furthermore, Mitra et al. [121] studied the effect of dielectric fluid on machining of γ-titanium aluminide alloy (Ti-44.5 Al-2 Cr-2 Nb-0.3B in %) on micro-EDM. The study compared the influence of operating factors on crater overcut dimensions in dry and EDM oil dielectric mediums. It was found that the micro-EDM in dry conditions can be efficiently applied for micro-machining of γ-titanium aluminide alloy without deformation in the workpiece. The results showed that the circuit capacitance of RC pulse generator was considerably affected the overcut of craters. Also, the crater depth formation by a single discharge dry-micro-EDM was relatively smaller than machining with dielectric oil medium. Chow et al. [132] studied the EDM process performance due to dielectric fluid of SiC powder added to pure water. It was found that MRR was increased when the SiC powder was added. Also, SiC powder generated minor carter.

Yan et al. [133] evaluated the machining performance of EDM and studied the effects of the dielectric with urea addition on surface modification of pure titanium metal. They explored the influence of machining parameters including the dielectric type, *Ip*, and *Ton* on MRR, EWR, and Ra. Moreover, they determined the elemental distribution of nitrogen on the machined surface to assess the effects on surface modification. It was revealed that the MRR and EWR were increased with adding urea into the dielectric fluid. In addition, MRR and EWR dropped as the *Ton* increased. They have also reported that the machined surface wear resistance was improved due to migrated of nitrogen elements to the workpiece surface which made TiN a hard layer. Chow et al. [134] developed a revised EDM process by altering the discharging circuit and introducing a new horizontal rotating electrode mechanism. The study measured the process by measuring quantitatively and qualitatively using different dielectric fluids including kerosene with and without aluminum and SiC powder. The study investigated the influence of the dielectric fluid on material removal depth, EWR, the slit expansion, Ra, and the waveform of the discharging condition for titanium alloy in the revised EDM. It was found that dielectric fluid kerosene mixed with either Al or SiC powder increased the material removal depth and the Ra. Specifically, SiC/kerosene mixture resulted into a better material removal depth than Al/kerosene mixture. Furthermore, kerosene with either Al or SiC powder mixture extended the gap between the tool and the workpiece. The largest *G* was generated in the case of Al powder/kerosene mixture. Al powder with kerosene found to be the best selection to be used for titanium processing. Also, Chen et al. [90] inspected the machining characteristics of Ti–6A1–4V in EDM with kerosene and distilled water as dielectrics. It was revealed that using the distilled water as dielectric fluid rather achieved higher MRR and relatively lower EWR than using kerosene. In both of dielectric fluid medium carbide (TiC) and oxide (TiO) were formed on the workpiece surface.

Wang et al. [124] investigated the effects of electrical conductivity, oxidability, and viscosity of dielectric fluid on the EDM of titanium alloy. They have developed a compound dielectric with optimal processing effect. They have studied the MRR, EWR, and Ra for titanium alloy machining using the EDM in three dielectric mediums, namely, the developed compound dielectric, distilled water, and kerosene. It was found that the compound dielectric fluid achieved higher MRR and a lower REWR than that in kerosene. Koll and Adepu [135] investigated the influence of additives in dielectric fluid on process parameters. It was revealed that the MRR was higher and EWR and Ra were lower for machining titanium alloy in EDM with additives added in dielectric fluid compared to dielectric fluid without additives. Furthermore, the formed recast layer when adding additives to the dielectric fluid was smaller than the formed layer in dielectric medium without additives. Also, the machined surface was uniform and cracks were relatively less with additives. It was notified that MRR, Ra, and EWR were increased as the *Is* was increased. Izman et al. [95] studied the process performance of EDM for Ti6Al4V. The influence of dielectric medium on the process performance was compared for dielectric fluid of kerosene with and without adding multi-walled carbon nanotube. The research work studied the effects of *Ton*, *Toff*, and *Ip* on MRR and Ra for the two dielectric fluid conditions. It was found that addition of multi-walled carbon nanotubes to dielectric improved the MRR and Ra and reduces the white layer thickness. Rongyuan et al. [144] studied the influence of dielectric viscosity on the amount of discharge debris thrown out and the force needed and the thermal conductivity of dielectric. The paper introduced the trends of MRR, REWR, and Ra when changed the dielectric viscosity during machining of titanium alloy using EDM process. The outcomes showed that the MRR was increased when the viscosity was increased but when it is increased excessively, MRR was reduced. EWR and Ra decrease as the viscosity rises. Finally, raise in the viscosity decreased the thermal conductivity of dielectric and lower cooling speed which led to produce less micro-cracks.

Abdulkareem et al. [145] studied the influence of electrode cooling on the immigration of elements from the tool to the workpiece surface. They used liquid nitrogen as a coolant for the electrode. *Is*, *Ton*, *Toff*, and *V* were considered as process parameters. It was found that the EDM process with electrode cooled by liquid nitrogen reduced material movement and diminishes the surface contamination of the electrode. Furthermore, the effect of electrode cooling on recast layers and micro-crack in EDM of titanium has been studied by Abdulkareem et al. [146]. The study considered current intensity, *Ton*, *Toff*, and *V* as working parameters. They studied the effect of electrode cooling on recast layers and micro-crack.

4.7 Other bodies of research on titanium and its alloys in EDM

Many studies are focused on several other issues related to EDM of titanium and its alloys. For example, Klocke et al. [83] compared three manufacturing technologies namely, milling, EDM, and ECM regarding rough machining of titanium and nickel-based blisks. Depending on the specific geometry, the most cost-effective technology in case of Ti–6Al–4V was either milling or ECM. For Inconel 718S, EDM could be a better alternative particularly for smaller batch sizes. EMC was the best choice for large scale production. Fonda et al. [87] studied the influence of thermal and electrical properties of Ti–6Al–4V on the productivity of EDM. The study was measured the temperature for workpieces of various extend τ. Other studies concentrated on the required energy of the discharge pulse. For example, Mahardika et al. [147] presented a fundamental study of the total discharge pulse energy needed to machine different operations. The study proposed a (λ, θ and ρ) theory (where λ is thermal conductivity, θ is melting point, and ρ is the electrical resistivity of the workpiece). Based on the experimental results of machining stainless steel and other materials, they have found that the coefficient of correlation for each parameter from the (λ, θ, and ρ) theory was much greater than the λ, θ theory. The study compared the ease of machining for 12 workpiece materials machined using EDM; it was found that the Al was the easiest material to machine by EDM and extend W was hardest material to machine, according to the (λ, θ, and ρ) theory. Aspinwall et al. [116] have compared the machinability of γ-TiAl using many machining processes (namely, turning, grinding, HSM, drilling, EDM, and ECM). They have reported that surface integrity problems found in all processes except turn-milling which can provide cylindrical surfaces without crack.

Qin et al. [112] studied the new phase formed in the machined surface of Ti–46Al–2Cr intermetallic alloy induced by wire EDM. It was found that the new phase was existed in the machined surface is limited to around 70 μm thick. The study also proposed vacuum annealing process at 400–600 °C to eliminate this hydride induced by wire EDM. It was also found that the wire EDM induced micro-cracks that penetrate into matrix up to 10–30 μm. Shangping [148] presented detailed description of the surface tinting technique of the titanium alloy surface during EDM process.

Minami et al. [149] proposed coloring method for titanium alloy and studied the influence of the processing condition to the color tone for titanium alloy by using EDM process. It was found that the molten and re-solidified surface created by EDM process was colored straight away by the interference phenomena in the anodic oxide film formed with electrolytic affection. The thickness of the oxide film determined the color tone. They have reported that there was a possibility to give various kinds of colors by controlling the average working voltage. Minami et al. [150] investigated the coloring mechanism on the EDM surface by calculating the spectral reflectance of interference light based on the "multiple beam interference" theory. The results revealed that the color of the EDM surface strongly resembled the interference color of spectral reflectance. They have reported that the surface coloring by EDM was caused by an interference phenomenon in the anodic oxide film and the oxide film thickness depended on the average working voltage. In their study, Minami H. et al. [150] evaluated the properties of the colored surface and discussed the corrosion resistance, the weatherability, and the wear resistance of the colored surface. The surface colored due to the presence of an oxide layer had high corrosion resistance and excellent weatherability. Moreover, the wear resistance of the colored surface was improved as an additional effect of EDM. Yadav et al. [100] presented an experimental investigation for holes machining in aerospace titanium alloy workpiece using static electrode machining and EDM process. The study introduced a mechanism to hold and rotate the tool electrode replaced tool holder attached with EDM. The influence of processing parameters including *Is*, *Ton*, τ, and electrode rotation speed on performance parameters was introduced. They showed that the effect of rotating electrode machining has significant effect on the measured output response than the machining with conventional electrode holder.

Many developments were proposed connected with the EDM processes; Chow et al. [110] modified EDM by fitting a rotating disk as electrode (RDE). In the modified RDE-EDM, the electorate was located below the workpiece**.** They have showed authors reported that the MRR has great improvement in the modified process. The effects of *P*, *Is*, *Ton*, and electrode rotation on the MRR, EWR, slit expansion, the surface profile, and the recast layer of micro-slit machining were also investigated. The authors have successfully used EDM with RDE for micro-slit machining. The machined surface of the slit showed less cracking, less recast layer, and a smaller expansion of the slit with negative *P*. They have also showed that the optimal work parameters to obtain the smallest slit width were as follows: *Ip* of 0.06 A, *Ton* of 2 μm, and rotational speed of 20 rpm.

5 Discussion

Reviewing the publication related to the titanium and its alloys machining using the EDM process shows that the majority of the studies considered the influence of the working parameters on the output parameters mainly the MRR, EWR, and surface quality. Other bodies of research have been conducted to solve or study other issues, such as electrode material and its geometry, effect of EDM process on the titanium and its alloy properties and machined surface, combined and hybrid processes, and the dielectric fluid used in the process, among others. The researchers have paid more attention to the sinking EDM and wire EDM processes to obtain the optimal and near-optimal working parameters, which may be attributed to the popularity and application of these two processes. • The pictorial representation of the future research directions is shown in Fig. 11. The research directions can be classified into four broad categories and which will be further divided into sub-categories and are shown in Fig. 12.

Fig. 11 Future research areas in EDM field

6 Conclusions and future research direction

This review on the state-of-the-art studies on the EDM processes of titanium and its alloys leads to the following conclusions and future research trends:

- *Is* and *Ton* significantly affected the performance of the EDM process while machining the titanium and its alloys.
- MRR is mainly influenced by Ton and Is, whereas Toff has least effect.
- MRR is improved when the viscosity is increased; however, when it is increased excessively, MRR is reduced. EWR and Ra decrease as the viscosity rises.
- Low discharge energy generates surfaces with fine microstructure. High discharge energy results in more craters and cracks.
- Rotating electrode improves the MRR; however, it also results into high Ra.
- In wire EDM, the coated wires are observed to be better than the uncoated wires in terms of obtaining uniform surface characteristics.
- The review reveals that high discharge energy caused surface defects such as cracks, craters, thick recast layer, micro-pores, pin holes, residual stresses, and debris.
- The relatively short discharge duration with low Is range under the electrode negative P leads to titanium carbide layer with less crack surface.
- The recast layer thickness increases as the Is, Ton, and concentration are increased. The recast layer formation depends on types of material, machining P, and to some extent both V and Ip.
- The electrode size and G play a major role in determining the plasma characteristics in micro-EDM
- The process with copper electrode leads to higher MRR and lower EWR compared to the processes with brass and aluminum electrodes.
- The appropriate electrode material for machining of titanium alloys is copper-infused graphite.
- The EDM of titanium used the copper tool electrode in the water is more stable than in the oil and had a low electrode wear ratio.
- The review also reveals that the ultrasonic action has a substantial influence on the performance of the EDM process. The integration of EDM/USM process increases the MRR and decreases the thickness of the recast layer. This integration is very helpful in reducing the abnormal discharge and in improving the discharge efficiency.
- The performance of the EDM process specially the MRR is extremely improved by mixing certain powders into the dielectric fluid.
- The aluminum powder produces the best surface finish and surface topography, followed by SiC, Gr, Cr, and Fe in sequence.

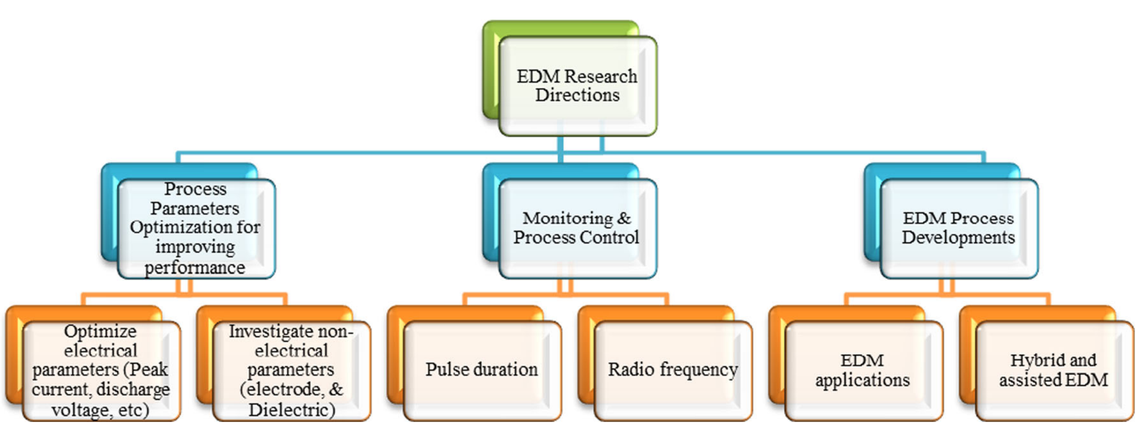

Fig. 12 Research direction classification

- Al powder with kerosene found to be the best selection to be used in the titanium processing.

7 Recommendations for future trends

In the light of the above conclusions, researchers need to pay more attention to the machining of different grades of titanium and its alloys using different EDM types under dielectric fluid with different material powders associate with magnetic field. Studies covering such important points are very lacking with literatures.

The great improvement of the performance revealed in the reviewed research is related to the EDM with ultrasonic action. Research trends may be directed toward the combination of the two processes. Moreover, other hybrid processes can also be investigated to get better results, such as laser beam machining with EDM.

• More attention are demanded to eliminate the limitation of miniaturization in micro-EDM. Low level of electric discharge energy is required to overcome this limitation. Furthermore, new techniques to avoid distortion of micro-workpieces are one of the necessary trends for future research. Micro-EDM still requires more level of precision and accuracy.

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