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A REVIEW ON MACHINING OF TITANIUM BASED ALLOYS USING EDM AND WEDM

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Abstract. The aim of this review is to present the consolidated information about the contributions of various researchers on the application of EDM and WEDM on titanium materials and subsequently identify the research gaps. The literature survey has been carried out from three perspectives such as application of EDM and WEDM on titanium materials, utilization of tools and techniques for correlating experimental results and application of products produced by EDM and WEDM. Three main research areas has been identified. First, the application of EDM and WEDM on titanium materials mainly TiNi based alloys. Second, the utilization of advanced tools and techniques such as artificial neural network (ANN), advanced particle swarm optimization (PSO) and tabu enhanced genetic algorithm (GA). Third, the study and analysis of surface integrity in EDM and WEDM on titanium materials. In addition, the paper has also evolved the future research directions. The paper has been concluded by indicating the future research directions for the research gaps identified during this literature survey.

1. INTRODUCTION

The titanium based alloys are advanced materials used in wide range of engineering applications. The utilization of these alloys comprises of multi-disciplinary fields such as aerospace, spacecrafts, marine, automobile, gas-turbine engine, military ballistic armor, nuclear, chemical vessels, sports and medical applications. The percentage of these alloys utilized in the aero engines are shown in Fig. 1 [1]. It is mainly owing to their high strength at low to moderate temperature, light weight, excellent corrosion and wear resistance, good fatigue property, highly biocompatible and so on. However, the properties of these alloys are significantly affected by the characteristic features such as susceptible to oxygen, nitrogen and the presence of other impurities [2].

The titanium alloys are categorized into three groups based on composition and resultant predominant constituent phase at room temperature. The alloy types comprises of α structure, ($\alpha + \beta$) structure and α structure, the commercial titanium contains small amount of a or ($\alpha + \beta$) matrix. Heat resistant (up 700-800 °C) alloys of aluminides (α-phase, γ-phase), shape memory alloys (SMAs) containing TiNi and fire safety eutectoids [2,3]. The vanadium free titanium materials has superior mechanical and biocompatiable properties owing to their use in artificial hip joints [4]. These applications demand for the manufacturing of Ti based devices and micro-components. Hence machinability study of Ti based alloys is an thrust area of the manufacturing sector.

TiNi based alloys are the important class of titanium alloys, generally considered as shape memory alloys (SMAs). TiNi based SMAs are highly biocompatible with better shape memory properties and 8% recoverable strain. Hence, they are widely

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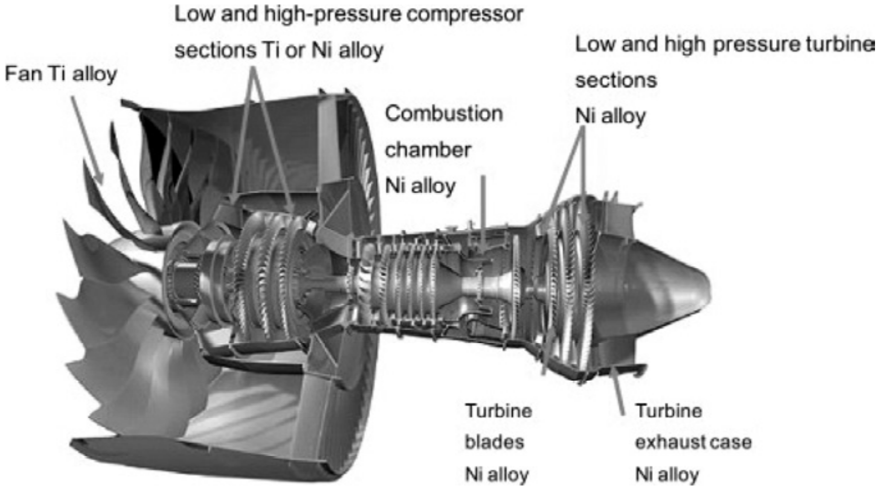

Fig. 1. Ti alloy in an aero engine [1]. Reprinted with permission from International Journal of Machine Tools and Manufacture, 51, 250-280 (2011).Copyright 2011, Elsevier.

used in sensors, actuators and the effect of shape memory property is utilized in the thermal actuators, sensor flaps of air conditioners, water flow control valves and automatic adjusting oil valves [5]. In the past few years, SMAs are used in many engineering applications with different shapes like tube, foils, tape and for medical application guide wire for catheter [6]. The machining of SMAs is relatively important and integral part in the production of components for utilizing in engineering applications.

The machining of titanium materials is extremely difficult because of low thermal conductivity and high chemical reaction [7]. The productivity and surface integrity are identified as important phenomena in the process of machining [8]. Higher productivity can be achieved by using high cutting speed. The machining of these materials at higher cutting speed is very difficult due to greater tool wear (rapid chipping at cutting edge, catastrophic failure and plastic deformation of the cutting edge), higher surface hardness, severe microstructure alteration and poor surface quality.

During conventional machining of these materials, higher tool wear and lower surface quality are commonly observed phenomenon, due to their higher strain hardening effect, pseudoelastic behavior and high toughness [9-11]. The difficulties of NiTi alloys occurred during the conventional machining is observed from Fig. 2 [11]. To overcome these problems, they can be effectively machined by non-conventional machining processes such as laser machining, Water Jet Machining (WJM), Electro Discharge Machining (EDM) and Wire-EDM (WEDM). EDM is an advanced method and it is introduced into dental technology owing to the manufacturing titanium implant observed from Fig. 3 [12]. The highly biological and corrosion resistant surfaces can be manufactured from the EDM. Hence, the present proposed study is concentrated on WEDM of titanium based alloys. The EDM and WEDM machining of different titanium based alloys used in previous studies is summarized in Table 1.

The material removal rate and surface integrity are directly proportional to the productivity and quality of the component in any manufacturing industries. The quality of component plays vital role in the performance of the product. Surface integrity which in terms of surface roughness, topography, surface hardness, residual stresses, phase transformation and microstructural changes, which are the most relevant parameters quantifies the quality of the component in the machining. Many researchers addressed the study on machining of Ti based alloys using EDM and WEDM by considering the few parameters. However there is no sufficient data available on complete WEDM of Ti based alloys. Kao et al. [13] optimized the EDM process parameters on EWR, MRR and surface roughness of Ti6Al4V alloy using Taguchi and grey relation technique. Hascalik and caydas [14] studied the surface integrity property of Ti6Al4V alloy by EDM and abrasive electrochemical grinding (AECG). The damages which has occur by EDM can be reduced by the AECG and to achieve good surface finish. Klocke et al. [15] summarized the fatigue strength and surface property of EDMed Ti6Al4V alloy. The EDMed specimen has better fatigue life compared to grinding. Yilmaz et al. [16] studied the effect of multichanel electrode on the hardness of drilled hole performance. The nanostructured oxide layer formed during the EDM increases the biocompatiability of the titanium material [17]. The better surface finish

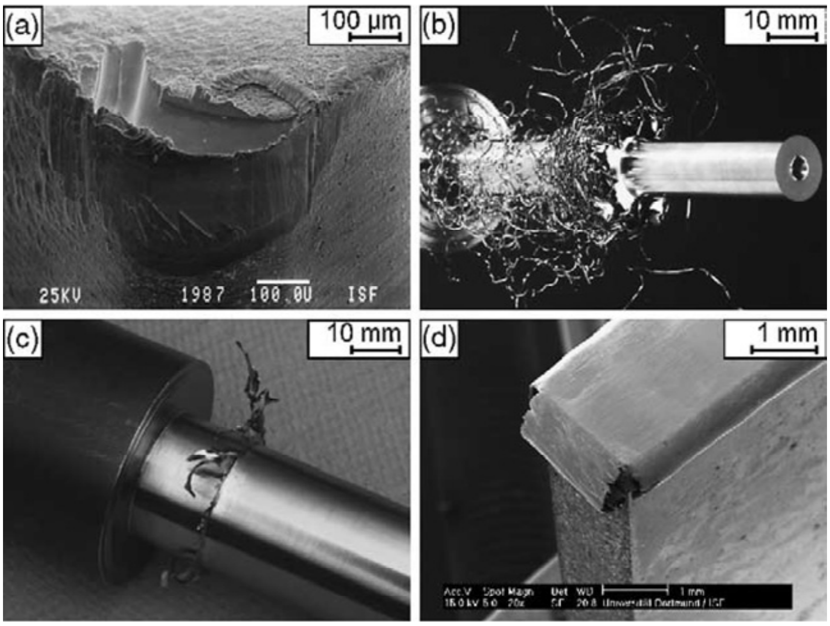

Fig. 2. Difficulties occurred when conventional machining of NiTi alloy a) High tool wear b) Adverse chips c) Formation burr after machining d) After grinding [11]. Reprinted with permission from Materials Science and Engineering: A, 378, 180-184 (2004).Copyright 2004, Elsevier.

with neutral residual stress and lesser recast layer thickness can be achieved on Ti-6Al-2Sn- 4Zr-6Mo titanium alloy by two trim passes of the WEDM [18]. Harcuba et al., [19] made an investigations of the biocompatibility of Ti6Al4V alloy after the surface machining by the electric discharge machining (EDM) process. The surface modification considered to be promising improvement to orthopedic implants and bone tissues. In this context, the survey is made on responses of machining of Ti based alloys and the statistical techniques used to correlate the experimental study.

2. MATERIAL REMOVAL RATE (MRR)

The MRR is a significant parameter which affects the productivity of any manufacturing industry. MRR is the amount of material removed from the work piece under the working time (mm^3/min or mg/min). It defines the characteristic efficiency of the machine. The present survey is made on the MRR for Ti based material machined by EDM and WEDM at different machining conditions. During the EDM of Ti based materials the MRR significantly influences on discharge current and duty factor of about 74 and 23 percent respectively [13]. From the available literature it was found that, the higher MRR can be achieved by the positive polarity of the electrode. The positive polarity of the electrode is preferred in EDM and WEDM with kerosene as dielectric fluid. It is primarily due to the fact that, carbon particles adhered to the surface of the tool and forms layer of carbon. The carbon layer protects the erosion of tool electrode [20].

The MRR is increased with the increase in discharge current (power). It is due to the strengthened discharge energy melts and removes the material more easily by the higher current density. In principle, the thermal conductivity and melting temperature of the material suits the MRR. The MRR will increases with the certain value, further increase in pulse on time duration leads to the fall of MRR. This is due to the expansion of plasma channel. At high pulse duration, the localized temperature increases. It leads to decomposition of carbon, that is bonded on the electrode surfaces. Hence the dis-

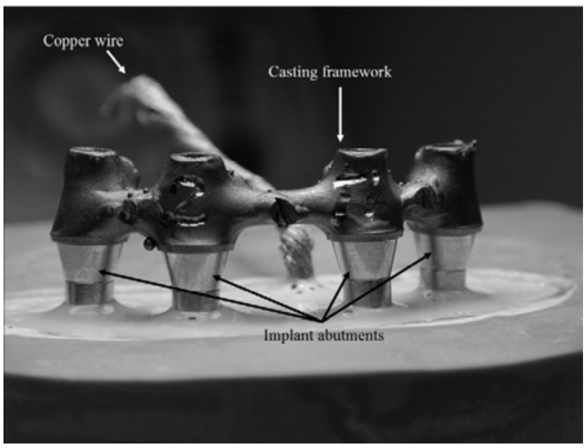

Fig. 3. Titanium dental implant machined by EDM [12]. Reprinted with permission from Dental materials, 23, 601-607 (2007).Copyright 2007, Elsevier.

Table 1. EDM and WEDM of titanium alloys.

Authors	Process	Material	Tool material	Brief contribution
Lin et al., [23]	EDM	$Ti_{49}Ni_{51}$, $Ti_{50}Ni_{50}$ and $Ti_{50}Ni_{40}Cu_{10}$ alloys	Copper	EDM characteristics of TiNi shape memory alloys have been investigated
Kuriakose et al., [64]	WEDM	Titanium alloy	Zinc coated brass	The data mining approach is adopted to decide the optimum parameters
Sarkar et al., (2005) [65]	WEDM	γ-titanium aluminide alloy	Brass	Optimized the process parameters using the constrained optimization and Pareto optimization algorithm.
Sarkar et al., [66]	WEDM	γ-titanium aluminide	Brass	Developed appropriate machining strategy for maximizing the criteria like higher cutting speed and best surface finish using neural networks to machine ã titanium aluminide through WEDM.
Chen et al., (2007) [21]	EDM	$Ti_{50}Ni_{49.5}Cr_{0.5}$ and $Ti_{33.5}Ni_{49.5}Zr_{15}$ alloys	Copper	Investigated the effect of the machining characteristics of TiNiX ternary shape memory alloys.
Hascalik et al., (2007) [67]	EDM	Ti–6Al–4V	Graphite, copper, and aluminium	Explored the influence of EDM parameters and different electrode material on various aspects of the surface integrity of Ti-6Al-4V
Yan et al., (2007) [68]	WEDM	Tool steel, Titanium alloy and tungsten carbide	Brass	Developed a high-frequency power supply for surface quality improvement
Chen et al., (2008) [69]	EDM	NiAlFe and TiNiZr SMA	Copper	Studied the machining characteristics of NiAlFe shape memory alloy
Aspinwall et al., (2008) [29]	WEDM	$\alpha + \beta$ titanium alloy (Ti–6Al–4V) and Inconel 718	zinc coated brass	Investigated the recast layer thickness which is 11 μm during WEDM of Ti6Al4V and Inconel 718 material and it can be eliminated by etching operation
Fonda et al., (2008) [38]	EDM	Ti–6Al–4V	Copper	Determined the temperature distribution in material during EDM and optimized the parameters to improve the productivity and quality
Hsieh et al., (2009) [33]	WEDM	$Ti_{35.5}Ni_{49.5}Zr_{15}$ and $Ti_{50}Ni_{49.5}Cr_{0.5}$	Brass	Wire electro-discharge machining (WEDM) characteristics of TiNiX ternary shape memory alloys (SMAs) were studied
Yan et al., (2009) [70]	WEDM	Tool steel SKD11, titanium alloy and tungsten carbide	Brass	A new fine finish power supply in Wire-EDM is developed and its applications were studied.
Sarkar et al., (2010) [71]	WEDM	γ-titanium aluminide	Brass	Presented an integrated approach to optimize WEDM of γ titanium aluminide.
Gill et al., (2010) [42]	EDD(Drilling)	Ti-6246	Electrolytic copper	Studied the EDM Machinability test on titanium alloys which has undergone Deep Cryogenic Treatment

Abdulkareem et al., (2010) [72]	EDM	Ti-6Al-4V	Copper	Studied the effect of process parameters on the electrode wear in EDM of Titanium alloy.
Yilmaz et al., (2010) [16]	EDM	Inconel 718 and Ti-6Al-4V alloys	Brass and copper	A comparative experimental investigation of electrical discharge machining fast hole drilling of aerospace Inconel alloys were made.
Rahman et al., (2010) [35]	EDM	Ti-6Al-4V alloys	Copper and tungsten	Experiments have been conducted to investigate the effect of peak current, pulse on time and pulse off time on the performance characteristics.
Peng et al., (2010) [17]	EDM	ASTM F67 Grade IV Ti sheet	Copper	Effects of electrical discharging on formation of nonporous biocompatible layer on titanium were studied.
Kao et al., (2010) [13]	EDM	Ti–6Al–4V alloys	Electrolytic copper	Optimized the machining process parameters to improve the performance characteristics of electrode wear ratio, MRR and surface roughness
Klocke et al., (2011)[73]	Grinding and WEDM	Ti6Al4V	N/A	Compared the fatigue life of WEDM machined and grounded samples.
Khan et al., (2011) [74]	EDM	Ti-15V-3Cr-Al-Sn	copper	Predicted the surface roughness of Ti-15-3 alloy in EDM using Artificial neural network model
Antar et al., (2011) [18]	WEDM	Ti-6Al-2Sn-4Zr-6Mo and Udimet 720 nickel based super alloys	copper wire with CuZn50 coating and copper core with a double layer zinc rich (60% wt) outer coating	Studied the effect of wire electrode on the productivity, surface roughness and residual stresses.
Sen et al., (2012) [22]	EDM	Ti-6Al-4V-XB (*X*= 0.0, 0.04, 0.09)	Copper	Improved the machining property of Ti-6Al-4V Alloys by the addition of boron content and verified addition of boron on the effect of MRR and tool wear.
Gu et al., (2012) [24]	EDM	Ti-6Al-4V alloys	Copper	Performance of bundle electrode is compared with solid electrode for developing the high performance and cost effective of Ti6Al4V alloy
Harcuba et al., (2012) [19]	EDM	Ti-6Al-4V alloys	Graphite	Surface treatment of Ti-6Al-4V alloys done with EDM for Orthopedic applications, properties studied after surface treatment

charge energy of the electrode is reduced and lower MRR is attained at high pulse duration.

MRR may alter in the WED-Machining that depends on the electrode material, melting temperature of the electrode and electrode wear rate. The discharge energy increases with the growing pulse duration. It causes the feed rate of a wire electrode leading to melting and evaporation of material. The increase in discharge current apparently increases the current density and advances the impulsive force of the expanded dielectric medium owing to higher MRR [21]. The MRR is directly proportional to the discharge pulse energy. On the other hand, pulse energy depends on the voltage or capacitance. Thus, higher the voltage wider the gap formation leads to high discharge. The capacitance determines the frequency, larger crater forms at lower frequency. Hardness and melting temperature of the material affects the MRR. The higher MRR can be achieved when material hardness and melting temperature is low [22]. Material with high melting temperature and higher thermal conductivity causes more heat transfer of discharge energy to the nearby matrix, hence lower MRR is attained [23].

As discussed above the pulse duration and discharge current significantly affect the MRR, higher MRR is achieved by the increase in pulse duration. It's mainly because the accumulated discharge energy melts and evaporates the material. The thermal energy of the spark causes the intense heat energy condition of the work-piece material. Yilmaz and Okka [16] discussed the effect of single and multi-channel electrodes on MRR made of copper and brass materials. The single channel copper electrode has higher MRR compared to multichannel copper and brass electrode. The flushing cleans the discharge gap and often reduces the frequency, because of fast recovery of insulation in multi-channel electrodes. This results in less material removal from the surface. Brass electrode is more efficient to obtain higher MRR because of low thermal conductivity and does not absorb much heat.

Gu et al. [24] studied the EDM of Ti-6Al-4V alloy with the bundle die sinking electrode and performance compared with the solid die sinking electrode. During machining with both the electrodes, MRR increases with the increase in peak current. At higher current (>57 A), MRR decreases with solid die sinking electrode and at peak current of 63 A, the damage of work-piece and electrode occurs. But the bundle electrode is stable to discharge energy causing dense material melting and evaporation, thus higher MRR can be achieved. The more carbon particles were deposited on the solid electrode surface than the bundle electrode. The gap diminishes the insulation effect of the dielectric medium leading to unstable discharge because of limited flushing.

The MRR varies with dielectric fluid usage, when using deionized water as dielectric the MRR increases linearly with the pulse on duration. When kerosene is used as dielectric fluid, MRR increases till the optimum point and further reduces. In addition the electrode wear ratio (EWR) increases with the pulse on time duration but when using deionized water the EWR is relatively less compared with the kerosene [25]. Lin et al. [26] also studied the MRR for combined EDM with USM of Ti6Al4V alloy by using the kerosene and deionized water with SiC abrasive concentration as dielectrics. Thus the abrasive enhances the gap between the electrode and work-piece causes higher MRR. It is observed from Fig. 4 that the MRR has reached maximum when the 90 g/l SiC concentration dielectric fluid is used and MRR is higher for distilled water compared to kerosene. The MRR is reduced with the further increase in concentration because of dense SiC particles accumulated in the interelectrode gap causing an unstable discharge. If aluminium particles used in the kerosene dielectric, MRR reaches an optimum value at lower concentration because of its light weight and best integration in the kerosene [27].

During the EDM of TiNi based alloys the MRR increases with pulse duration later MRR was found to be decreasing. Further increase in pulse duration lead for constant MRR because longer pulse

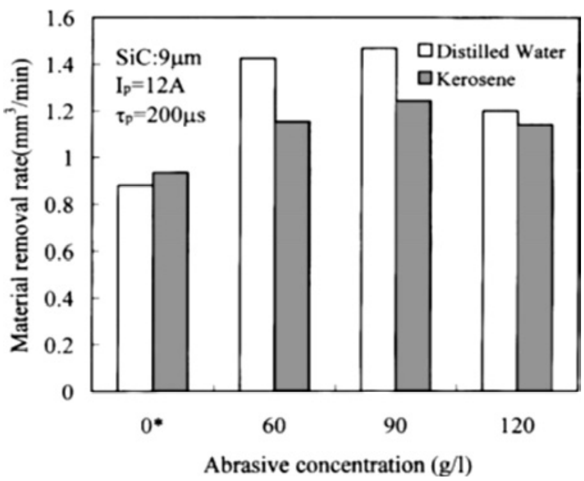

Fig. 4. Effect of SiC concentration on MRR using combined EDM with USM on Ti6Al4V alloy [26]. Reprinted with permission from Journal of Materials Processing Tech., 104, 171-177 (2000).Copyright 2000, Elsevier.

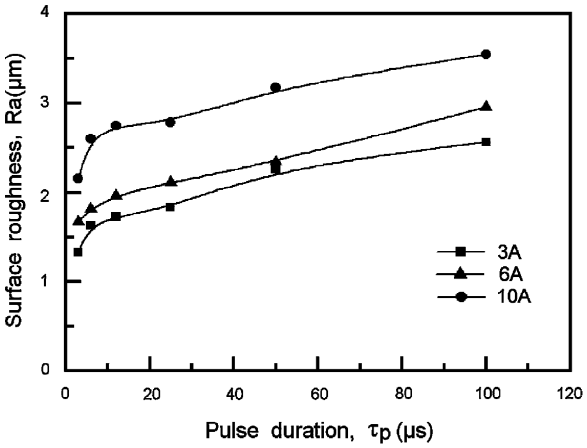

Fig. 5. Effect of pulse duration on surface roughness for various peak currents [21]. Reprinted with permission from Materials Science and Engineering: A, 445-446, 486-492 (2007).Copyright 2007, Elsevier.

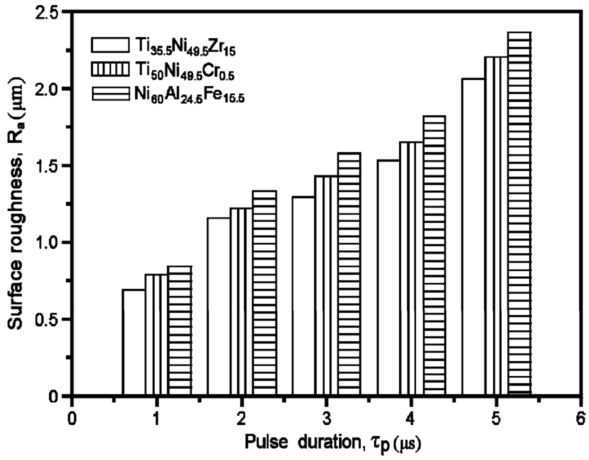

Fig. 6. Surface roughness versus Pulse duration of WEDMed TiNi based alloys [33]. Reprinted with permission from International Journal of Machine Tools and Manufacture, 49 509-514 (2009).Copyright 2009, Elsevier.

duration expands the plasma channel causing the decrease in energy density [23]. With respect to the machine feed rate, the MRR has increased during the WEDM of Ti6Al4V alloy [28]. In addition, pulse duration also increases with MRR by the expansion of discharge column and it is promoted by the induced energy.

3. SURFACE INTEGRITY

Surface integrity is an intrinsic factor which is affected by the machining conditions and indicates the machined surface and subsurface. The surface integrity is a major contributing factor in processing and performance of the part. The surface integrity comprises of (a) surface roughness; (b) surface morphology; (c) hardness; (d) residual stresses; (e) recast or white layer formation. The quality of surface is very much essential in performance, preventive, life costs, period of time and reliability of the products. Non-conventional machining is meant for the better surface integrity and higher productivity. This technique is rapidly growing in microcomponent manufacturing industries [29]. The surface in non-conventional machining is relatively less affected by the phenomena such as defects, plastic deformation, cracks, phase transformation, work hardened layer, residual stresses compared to conventional machining.

The machined components having good surface quality are required for majority of the applications [30]. The study of surface integrity concerned on alterations occurred on the machined layer and their effect on the properties of material. The surface texture of the machined surface is expressed in terms of waviness and roughness. The changes occurred during machining is surface hardness and other mechanical properties. This may be due to the residual stresses, metallurgical alterations such as microstructural, grain size, precipitation and localized thermo mechanical phase transformation contributes to the performance of component [31]. Many researchers have studied on surface integrity of the machined parts of Ti based alloys and then have been discussed further.

3.1. Surface roughness

Surface roughness is an important parameter influence on the performance of the machined components, further depending upon the type of contact, accuracy, friction and deformation. There are number of machining parameters which quantify the surface roughness such as the amplitude parameters that characterizes the surface topography. Surface deviation characteristic is most widely used parameter as the arithmetic mean average roughness [32]. The selection of EDM or WEDM parameters is an important criterion in achieving better surface finish for Ti based materials. Few authors have discussed the effect of parameters on the surface roughness [32,8,29,18].

The surface roughness in EDM depends on the intensity of the spark and the size of the crater produced during the machining at different range of pulse duration or discharge current. The surface roughness of EDMed Ti6Al4V alloy is significantly affected by the discharge current (67%), duty factor (17%),

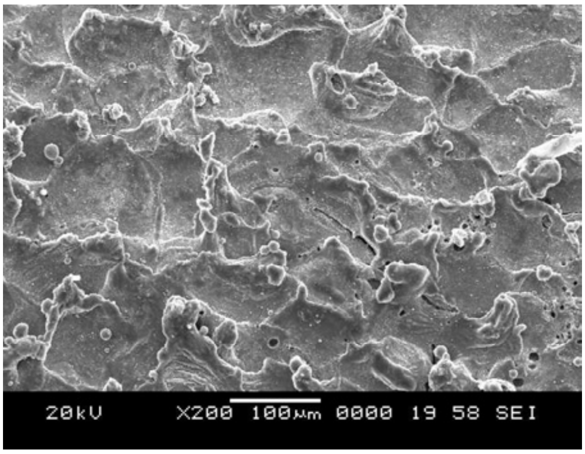

Fig. 7. Crater formation on the machined surface of TiNiCu alloy peak current-3 A, Pulse on time-40 μs.

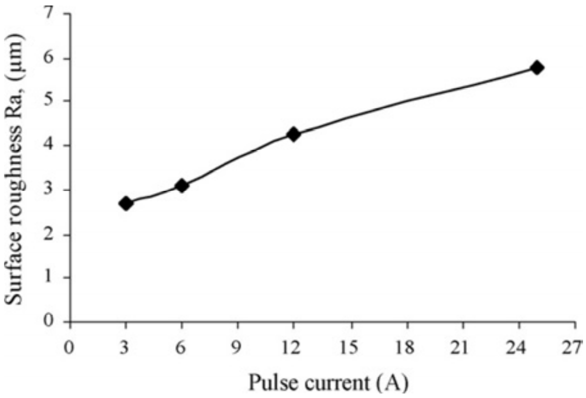

Fig. 8. Effect of peak current on surface roughness of EDMed pure Titanium [14] Reprinted with permission from Journal Of Materials Processing Technology, 190, 173-180 (2007).Copyright 2007, Elsevier.

and pulse duration (14%) [13]. From the study it is clear that the surface roughness is mainly varied by the discharge current followed by pulse duration. For the better surface roughness, lower discharge current and lower pulse duration is required. The surface roughness is also affected by the selection of tool material to machine Ti6Al4V alloy. The pulse duration affects the surface roughness, the increase in pulse duration, surface roughness increases for the Ti and TiNi based materials as observed from Figs.5 and 6. By increasing the pulse duration feed rate of wire electrode increases and extending the pulse duration to allow greater discharge energy melt and penetrate into the surface of work-piece material forms the deeper craters [21,33,34].

The surface roughness increases with the discharge current for any electrode material. As observed from Figs. 5 and 6, increasing discharge current causes the increase in the discharge energy, density of sparks and impulsive forces leading to deeper and larger crater formation on the machined surface. After the melting the spilled molten material solidifies on the periphery of the craters by the dielectric fluid causing higher surface roughness (Fig. 7). Increase in discharge current increases the strike rate of the spark on the machining surface and deterioration of surface occurs. Hence surface roughness increases with the discharge current (Fig. 8). The aluminium electrode exhibits better surface finish compared to graphite and copper electrodes [14].

The better surface finish can be achieved at higher values of servo speed. Higher values of servo speed produce rapid erosion of particles from the workpiece material surface. An increase in servo voltage increases the surface roughness due to more number of ions and electron collision takes place resulting in high MRR. For the better surface finish low value of servo voltage is to be employed.

The increase in pulse off time decreases the surface roughness. The pulse off time must be sufficiently long to acquire uniform erosion from the work piece otherwise, non uniform erosion takes place on machined surfaces. The longer pulse off time furnishes the better cooling effect and enough time to flush away the debris, melted material from the surface and inter electrode gap. In apparent, better surface finish is achieved by the longer pulse off time with the desired discharge current [35].

The dielectric pressure affects the surface roughness by the removal of particles and melted droplets from the machined surface. The sufficient flushing pressure is required to flush away the debris and molten metal from the surface, yielding for better surface finish. The flushing pressure can control the temperature of the medium and the dielectric acts as a coolant. If the pressure is less, heat transfer coefficient is low, it leads to increase the wire temperature which alters the wire tension and MRR. This ultimately leads to high surface roughness. Therefore high pressure is maintained for better surface finish [36,37].

The wire speed affects the surface roughness, higher the wire speed fastest crossing of the wire on the work-piece, less energy and lower material melting takes place. If the wire speed is lower, the melting of material is more due to higher energy and significantly higher MRR causes the higher surface roughness. Therefore optimum wire speed selection is an important need for better surface finish. Similarly the wire tension should set optimally. Lower wire tension causes vibration during the cutting and higher wire tension may subjected to breakage [36]. The machine feed also affects the surface

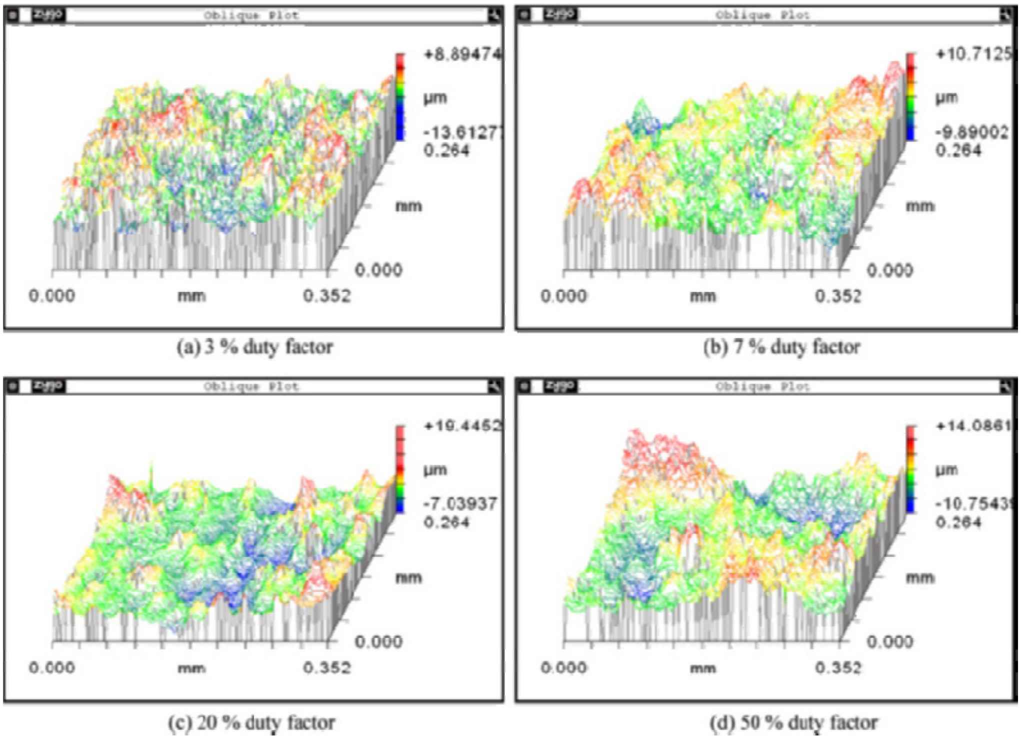

Fig. 9. EDMed Ti6Al4V surface profiles for different duty factors [38]. Reprinted with permission from J Mater Process Tech., 2 583-589 (2008).Copyright 2008, Elsevier.

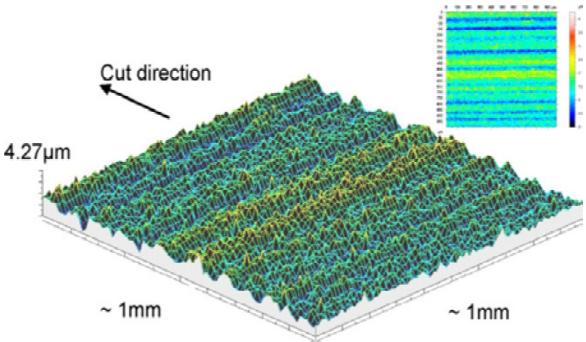

Fig. 10. Surface topography plot for Ti6Al4V peak current -400 A, pulse duration -1.8 µs after 4 passes (Ra-0.21µm) [29]. Reprinted with permission from CIRP Annals - Manufacturing Technology, 57 187-190 (2008).Copyright 2008, Elsevier.

roughness which in turn the wire tension and voltage significantly affects the surface roughness because of wire vibration during the machining and stronger electric field discharges spark at the same gap between the electrode and work piece induces coarse surface. Hence the better surface finish can be achieved with the lower machine feed [28].

3.2. Surface topography

The surface texture is produced on the machined surface and is strongly depends on the mechanical properties of the work-piece material and the machining conditions. This association is more pronounced in some materials and under certain machining operations. The surface topography as observed from Fig. 9, is varied with the duty- factor. At the lower duty factor, the approximately uniform surface appears as compared to higher duty factor. It is observed from the profile that the surface has more peaks and valleys at 50% duty factor. It is because of obtained higher temperature causes elevated arcing and slight damage to the surface of the tool electrode, further it leads to distortion of the machined surface. The lower duty factor is desirable for uniform surface [38]. The authors [29] achieved the better surface texture by the number of passes during the machining of Ti6Al4V alloy with no recast layer as seen from the surface profile Fig. 10.

The SEM micrograph depicts the EDMed surface of Ti6Al4V with the different dielectric fluids. The surface defects are elucidated from Fig. 11, micro cracks which occur in the distilled water used as a dielectric fluid compared to kerosene. This is due to the high thermal conductivity and the higher cooling rate of distilled water compared to kerosene. In addition, kerosene as the dielectric medium causes more noticeable cracks in the machined surface.

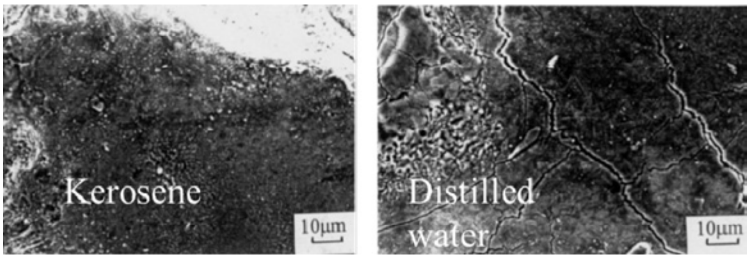

Fig. 11. SEM photographs of the crack distribution of an EDMed surface for different dielectrics (Peak current-24A, Pulse duration-100μs) [25]. Reprinted with permission from Journal of Materials Processing Technology, 87 107-111 (1999).Copyright 1999, Elsevier.

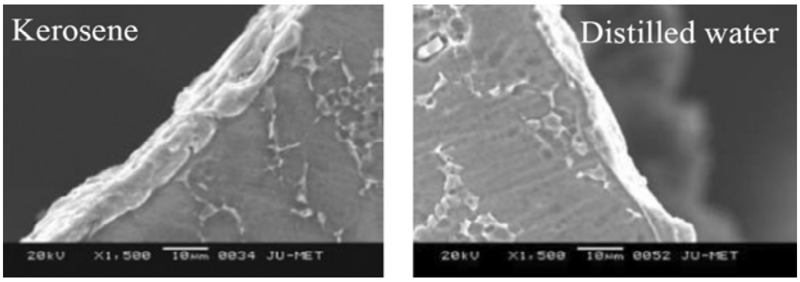

Fig. 12. White layer formation during EDM of Ti6Al4V at peak current-1.5A, pulse duration-10μs [43]. Reprinted with permission from International Journal of Advanced Manufacturing Technology, 48 557-570 (2010).Copyright 2010, Elsevier.

3.3. Surface metallurgy

During the Electro discharge machining the surface of the work-piece is exposed to thermal, mechanical and chemical energy, thus leads to the changes in the surface and subsurface properties because of high temperature around 10000 °C-12000 °C and quenching effect. The machined surface layer of the work piece always undergoes various kinds of metallurgical alterations. The surface integrity is affected by the plastic deformation during the machining. These changes occur in the material surface are influenced by the machining conditions such as electrical and non-electrical parameters. Few researchers [39,40] have studied the surface metallurgical aspects in the EDM and WEDMed Ti based alloys.

3.4. Layer formation

The characteristic surface layer is formed due to resolidification of melted material, high temperature and due to cooling effect. The machined surface can be categorized s white layer which is surface layer, below the white layerrecast layer and heat affected zone are present. It is essential to understand the layer formation and to minimize its thickness during the machining process. The layer formation occurs under the circumstances of higher discharge current and pulse duration with insufficient flushing conditions. The evaluation of layer formation is based on the discharge current, pulse duration, type of dielectric fluid and flushing pressure.

After the machining, the surface exhibits different property than that of the bulk material property. This alteration is due to thermal effects and phase change due to the rapid cooling in the process. These surface layers consist of the white layer and the recast layer which is higher hardness and different property compared to the bulk material. Sometimes the white layer is beneficial for particular applications such as dental or biomedical medicals but in applications such as aircrafts it is detrimental. This layer is brittle in nature, subsequently it is easy to engender the crack and grow into the bulk material. It also affects the surface and fatigue property of the material. Many researchers have investigated the formation of such layers in EDM of Ti based alloys [41, 9,16,29,21,42].

The white layer formation is less, when distilled water is used as dielectric fluid compared to kerosene as observed from Fig. 12. Further increase in pulse on duration the white layer thickness increases. It is due to the fact that increase in pulse duration increases the discharge duration time, that causes more melting and production of debris resolidification on the machined surface. The cooling rate is more in distilled water compared to kerosene, since the generated heat in the molten metal rapidly transfers into the dielectric distilled water. The probability of adherence of debris on the ma-

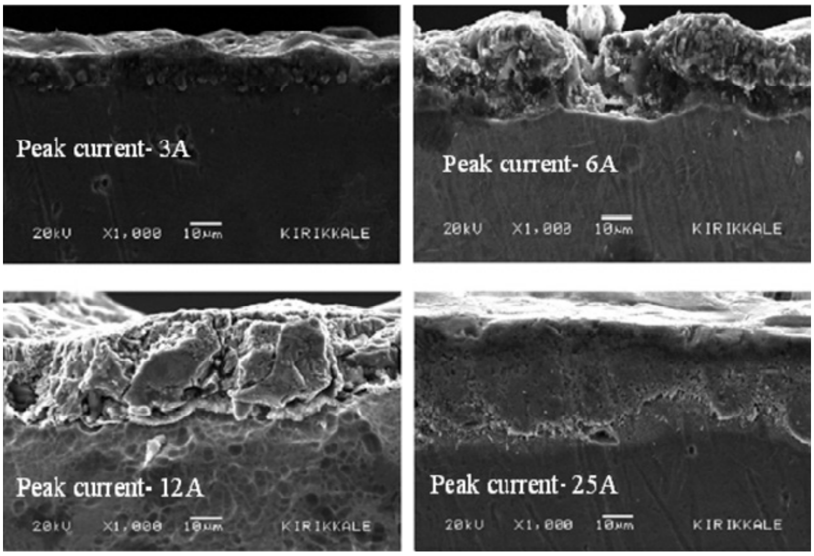

Fig. 13. White layer formation with variation in peak current [14]. Reprinted with permission from Journal Of Materials Processing Technology, 190, 173-180 (2007).Copyright 2007, Elsevier.

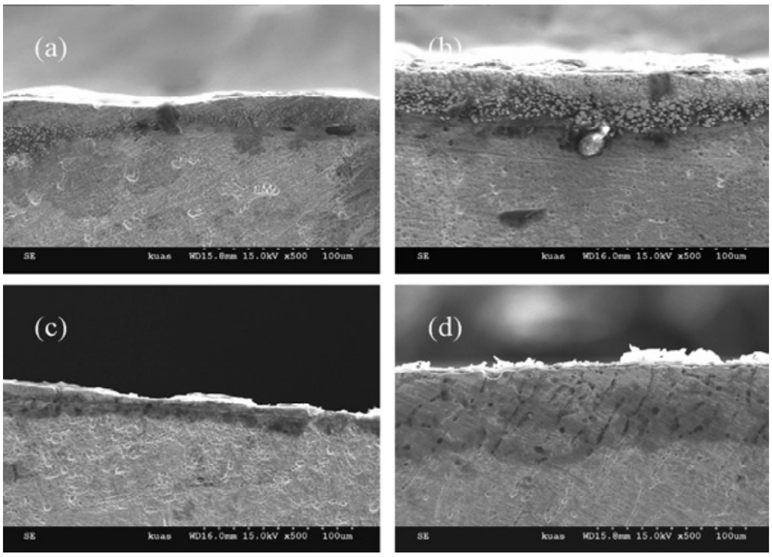

Fig. 14. An EDMed surface layer of Ti50Ni49.5Cr0.5 SMA at Peak Current-10A and Pulse durations (a) 3µs, (b) 6µs, (c) 12µs, (d) 50µs [21]. Reprinted with permission from Materials Science and Engineering: A, 445-446, 486-492 (2012).Copyright 2007, Elsevier.

chined surface is less resulting into lower white layer thickness. The additives in the dielectric relatively reduce the recast layer thickness compared to pure dielectric. The additives play a vital role to flush the molten material from the machined surface [43].

The effect of peak current on the recast layer increased with the increase in peak current, irrespective of the dielectric medium. Hascalik and caydas [14] has studied the effect of peak current on the recast layer thickness (around 11 mm) of Ti-6Al-4V component as shown in Fig. 13. It perhaps due to the production of deeper and larger craters, consequently melts more amount of material from the work surface and solidifies on the machined surface.

As observed from Fig.14 the large amount of recast layer formed on the TiNiCr EDMed surface by varying the pulse duration. Chen et al. [21] investigated the effect of pulse duration at 10 A of discharge current during the machining of TiNiCr alloy with kerosene as dielectric fluid. The surface recast layer initially increased from 3 to 6 µs of pulse duration. It is because, the ratio of positive electron flow in the plasma channel is more with the growing pulse duration. At pulse duration above 12 µs it was reduced to very less value, because at higher pulse duration violent impact force of the dielectric fluid was generated to flush away the molten material from the machined surface.

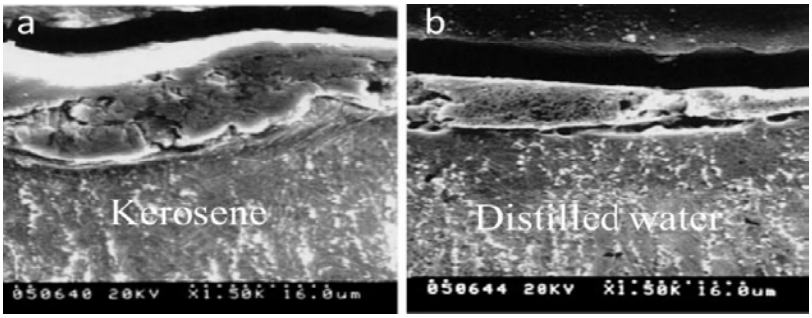

Fig. 15. Recast layer of Titanium alloy of peak current – 12A, pulse duration-100μs (a) EDM (b) EDM with USM [26]. Reprinted with permission from Journal of Materials Processing Tech., 104, 171-177 (2000).Copyright 2000, Elsevier.

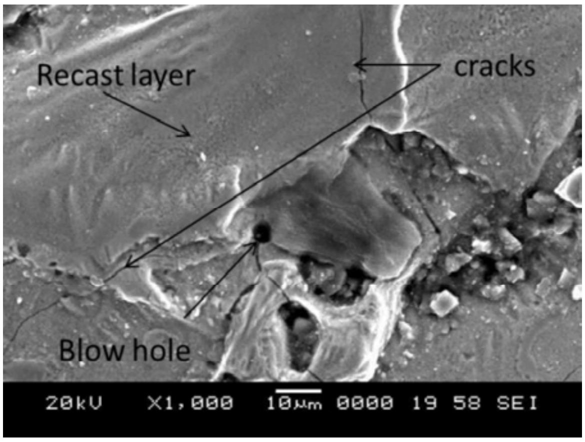

Fig. 16. Micrograph of $Ti_{50}Ni_{47}Cu_3$ alloy at pulse on duration – 48 μs and peak current -3 A.

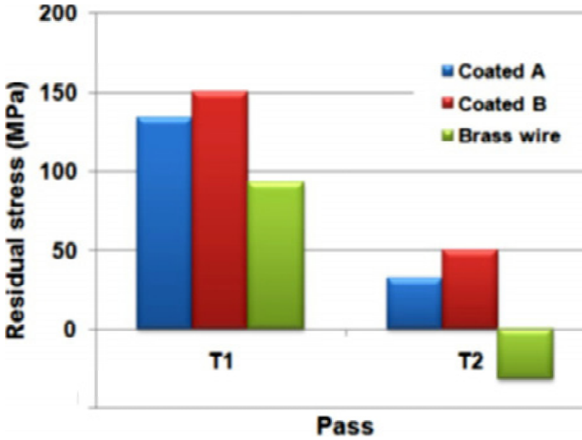

Fig. 17. Residual stress distribution of different tool electrode material [18]. Reprinted with permission from Procedia Engineering, 19, 3-8 (2011).Copyright 2011, Elsevier.

The author Lin et al. [26] have proved that the increase in pulse duration increases the recast layer thickness in any dielectric medium. The authors have also studied the effect of dielectric medium on recast layer thickness at pulse duration condition. It is observed from Fig. 15, the recast layer thickness is greater in conventional EDM as compared with the EDM assisted USM either with kerosene or distilled water. The reason is that the EDM assisted USM completely removes the debris and the molten material from the machined surface unlikely in the conventional EDM. The EDMed surface may contain enriched carbon, chemical alterations and implant living tissue interface which are potential in the orthopedics applications [40]. It is possible with optimum machining conditions and selecting suitable wire material, the recast layer thickness can be reduced.

3.5. Residual stresses

Residual stresses are generated on the machined surface, due to inhomogeneous temperature distribution and quenching effect by the dielectric fluid. The retained stress after plastic deformation in the machined workspace, contributing to tensile stresses in the subsurface of the material. It alters the microstructure of the underlying material subjected to high temperature. This is an instance of the components made from titanium alloys, which are widely used in aerospace, biomedical and bioengineering fields. The cracks produced in WEDMed surface are due to thermal stresses at machining conditions of pulse on duration 48 μs and peak current 3A of $Ti_{50}Ni_{47}Cu_3$ alloy as shown in Fig. 16. The cracks are originated in blow hole and white layer on the surface in the WEDM. This is arising at higher pulse durations rather than at lower pulse duration because thermally induced stresses are more at higher pulse durations [44]. The copper wire with a single layer zinc coating and double layer wires generate low residual stresses compared to brass wire [18]. The residual stresses are reducing the fatigue life of components.

Antar et al.[18] have made an attempt to reduce residual stress in WEDM of Ti6Al4V alloy at different machining passes of T1 (Voltage – 200 V, Ignition current – 4 A, on time - 0.05 μs, off time - 5.4

μs, flushing pressure – 1 bar, wire speed – 10 m/min, wire tension - 2.0 daN, and wire offset - 0.144 mm) and T2 (Voltage – 120 V, Ignition current - 4A, on time -0.4 μs, off time - 0.6 μs, flushing pressure – 1 bar, wire speed – 10 m/min, wire tension - 1.8 daN, and wire offset - 0.135 mm) with three different wires such as copper coated zinc wire (coated A), copper with double layer zinc coated wire (coated B) and the brass wire. The authors have notified the tensile residual stresses were generated during the WEDM at T1 condition, when same material passed through at T2 condition the stresses are reduced as observed in Fig. 17. The brass wire shows compressive stress in the material that is pre induced stress in the work piece material.

The tensile residual stresses originate the crack in the recast layer and penetrates into the bulk material when the stress outstrips the tensile strength of the material. The stresses increase due to the rapid heating and cooling of material by the dielectric fluid [14]. The residual tensile stresses remained in EDM processed specimens have poor fatigue strength. It can be eliminated by the heat treatment process [40]. The presence of carbon, carbides oxides in the surface layer is also observed. It may be due to the fact that, the tool electrode and the dielectric fluid cause inhomogeneity and high residual stresses in the material. The machined surface contains craters, blow holes, pock marks, melted droplets, debris and substantial layers, these may deviate the residual stress distribution to some extent [45].

During the EDM/WEDMing with distilled water as a dielectric medium, solidification of melted material is very rapid at higher temperatures and variation in machined surface layers. This layer appears as the recast layer below that presence of heat affect zone may be observed. The machined surface hardness varies in EDM/ WEDM with different dielectric fluid. The machined surface hardness increases up to a certain depth approximately 100 μm later it remains constant as that of bulk hardness.

During the electro discharge machining the formation of oxides and carbides on the machined surface is common due to the dissociation of dielectric fluid at higher temperature and the transfer of electrode material onto the machined surface. Lin et al. [23] concluded that the machined surface hardness of EDMed TiNi and TiNiCu alloy were increased from 200 Hv to 750 Hv, perhaps due to the formation of oxides TiO_2, $TiNiO_3$ and debris in the recast layer. The hardness varies from the machined outer surface to inner depth surface. Chen et al. [21] proved that the increase in near the outer machined surface hardness with the higher pulse duration and peak current. This hardening effect is because of the formation of oxides Cr_2O_3, ZrO_2, TiO_2, $TiNiO_3$, carbides like TiC in the recast layer. It is mainly during use of copper electrode and kerosene as dielectric fluid during the EDM of TiNi based ternary alloy. The same observation has been reported by the authors Hsieh et al. [33] during the EDM of TiNiCr and TiNiZr alloys.

Hascalik and Caydas [14] have studied the effect of tool materials on EDMed surface hardness. The outer machined surface hardness slightly varied with electrode material. This is owing to recast of melted electrode material on the machined surface. Yan et al. [46] stated that the machined surface hardness is high when use of urea solution as a dielectric fluid compared to distilled water in the EDM of pure titanium alloy. Aspinwall et al. [29] has studied the microhardness of the EDMed Ti6Al4V alloy and concluded that the alteration of machined surface has not occurred due to repeated passes. In addition, high voltage causes the increased microhardness up to depth of 5 μm.

4. Experimental modeling methods, techniques and analysis

Many researchers [47-53] correlated their experimental results with the input parameters using modeling techniques, and presented model for the output responses from the input parameters. The optimization of the output responses are be employed using optimization techniques such as Taguchi design, response surface methodology, factorial design, neural network, genetic algorithm, fuzzy logic, particle swarm optimization (PSO) and so on. The thermal related FEM based models like Ansys, CFD, LS Dyna, deform 3D and so on used for the analysis residual stress, wire breakage, recast layer with the combination of input parameters and certain constraints [54-57]. These tools give good results as that of experimental readings with very less errors. Some of the researches [58-60] done EDM/WEDM on real time estimation and online pulse train analysis system. Tomura and kunieda [61] analyzed the electromagnetic force in WEDM using 2D finite element methods.

The design of experiments is used to optimize the process parameters of WEDM for different alloys, which is reported in Table 2. Some of the authors are evolved the selection of optimization

Table 2. Material, process and process parameters of EDM and WEDM.

Authors	Process	Material	Tool	Process parameter
Lin et al., (2001) [23]	EDM	$Ti_{49}Ni_{51}$, $Ti_{50}Ni_{50}$ and $Ti_{50}Ni_{40}Cu_{10}$ alloys	Copper	Pulse current (A): 6-25, Pulse duration (μs): 3-100, Pause Duration (μs): -6-100, Gap voltage (V): 50, Electrode: Cu, Dielectric: Kerosene
Kuriakose et al., (2003) [64]	WEDM	Titanium alloy	Zinc coated brass	Ignition current(A): 8-16, Pulse duration(μs): 0.6-1.2, Time between the two pulses(μs): 4-8, Servo speed(mm/min): 4-12, Servo voltage(V): 30-60, Flushing(bar): 2-4, wire speed wire tension(kg): 1-1.2, Deionized water
Liao et al., (2004) [75]	WEDM	NA	NA	Pulse generating circuit (PS) - AC/DC, conductivity of dielectric K(μS/cm) - 15-45, Resistance in the circuit R(Ω) - 25-75, Capacitance in the circuit C (nF) - 0-20, Applied voltage (V) - 100-150,Feed rate of the table (mm/min)- 2-4, Pulse - off time (ms)- 4-8.
Sarkar et al., (2005) [76]	WEDM	γ-titaniumaluminide alloy (Ti-44.5 Al-2 Cr-2 Nb-0.3B (at.%))	Brass	Pulse on time (μs) - 0.8-1.6, pulse off time (μs) – 14-30, peak current (amp) – 120-220, wire tension (g) – 900-1380, Servo Volt (V) – 2-10, dielectric flow rate (kg/cm2) – 7-10.
Sarkar et al., (2006) [66]	WEDM	γ-titanium aluminide	Brass wire	Pulse on(μs): 0.8 – 1.6, pulse off(μs): - 14 – 30, peak current(A)- 120-220 Amp, Wire tension(gm)- 900 -1380, servo reference voltage(V)- 2 -10, dielectric flow rate (kg/cm^2)- 7 – 10.
Hascalik et al., (2007) [67]	EDM	Ti–6Al–4V	Graphite, copper, and aluminium	Discharge current (A) - 3 - 25, Pulse duration (μs) – 25-200, Pulse interval duration (μs) - 25 , Dielectric – Kerosene, Dielectric flushing - Side flushing with pressure, Dielectric flushing pressure (MPa) - 0.6.
Chen et al., (2007) [21]	EDM	Ti50Ni49.5Cr0.5 and	Copper	Discharge current (A): 3-19, Pulse duration (μs): 3-100, Pause Duration (μs): -6-100, Gap voltage (V): 50, Dielectric: Kerosene.
Yan et al., (2007) [68]	WEDM	Ti33.5Ni49.5Zr15 alloys	Brass wire	Pulse on time (μs)-1-8, resistance (ohm)-10-20, voltage (V)-110, pulse off time (μs)-1, wire tension (gf)-1700, wire feed (mm/min) - 5.
Bamberg et al., (2008) [77]	WEDM	Tool steel, Titanium alloy and tungsten carbide	Brass and molybdenum	Wire size(mm): 50-200, voltage(V): 130-150, Capacitance(nF): 3-68, Euro Supreme from Commonwealth Oil
Fonda et al., (2008) [38]	EDM	Gallium doped germanium	Copper	Current: 60 A, Voltage: 120V, servo voltage: 85 V, Discharge ON time: 20 μs

Yan et al., (2009) [70]	WEDM	Ti–6Al–4V and NAK 80 steel	Brass wire	Resistivity of water (kΩcm)- 100 -150, Current-limiting resistance (Ω)- 10 - 20 30, Pulse on-time (μs)- 1-3, Pulse off-time (μs) -2, Capacitance (nF)-1-10, Wire tension (gf) -1600 -1900, Offset (μm) -2-10.
Hsieh et al., (2009) [33]	WEDM	Tool steel SKD11, titanium alloy and tungsten carbide	Brass wire	Pulse duration (μs)- 1–5, Pause duration (μs)-5, Duty factor -0.6, Gap voltage (V) -50, Current (A) -15, Flushing pressure (kg/cm^2)- 5, Dielectric medium-De-ionized water
Bhaduri et al., (2009) [78]	EDM	$Ti_{35.5}Ni_{49.5}Zr_{15}$ and $Ti_{50}Ni_{49.5}Cr_{0.5}$	Copper	Pulse on time (μs): 10 – 30, peak current (Amp): 1 – 3, Duty cycle (%) : 59 –96, gap voltage (V): 22 -42
Abdulkareem et al., (2010) [72]	EDM	Titanium nitride-aluminium oxide composites	Copper	Current I (A): 4.3-6.3, Pulse on-time (μs): 3.3-5.3, Pause off-time (μs): 4.0-6.0, Gap voltage (V): 22-24.
Gill et al., (2010) [42]	Electric Discharge Drilling	Ti-6Al-4V	Electrolytic copper	Voltage (V)- 80, Current (A)- 10, Pulse on time (μs)- 15, Interval time (μs)- 15.
Weingartner et al., (2010) [79]	WED Dressing	Ti-6246	Zinc-coated brass	Peak current (A): 320A, Discharge duration (μs): 1.5, Pulse interval time (μs): 25, Wire speed (m/s): 20, Blasogrind HC5 oil.
Kao et al., (2010) [13]	EDM	N/A	Electrolytic copper	Discharge current (amp): 5-20, Open Voltage (V): 100-200, Pulse Duration (μs): 100-400, Duty factor (%): 30-70.
Sarkar et al., (2010) [71]	WEDM	Ti–6Al–4V	Brass	Pulse on time (μs): 0.25-1.05, peak current(A): 30-110, dielectric flow rate (L/min):2-10, and effective wire offset(μm): 40-80
Yilmaz et al., (2010) [16]	EDM	g titanium aluminide	Brass and copper	Discharge current (A): 20, Pulse duration (μs): 30, Pulse interval (μs): 23, Dielectric: De-ionized water, Dielectric pressure (bar): 75, Electrode rotation speed (rpm): 200, Electrode polarity: negative
Rahman et al., (2010) [35]	EDM	Inconel 718 and Ti-6Al-4V alloys	Copper tungsten	Peak current (Amp): 2 -30, pulse on time (μs): 10 -400, Pulse off time (μs)-50-300. Flushing pressure(Mpa)- 1.75, Applied voltage (V)-120, Servo voltage (V)-70, Dielectric –Kerosene
Cheng et al., (2011) [80]	EDM	Ti-6Al-4V alloys	Copper	Current (A): 0.11 -0.84, Pulse on (μs): 10 -100, Pulse off (μs): 5-20.
Khan et al., (2011) [74]	EDM	Ti-6Al-4V alloys	Copper	Peak current (A): 1-29, pulse on (μs): 10-350, pulse off (μs): 60-300, Servo voltage (V): 75-115.

Antar et al., (2011) [18]	WEDM	Ti-15V-3Cr-Al-Sn Annealed Ti-6Al-2Sn-4Zr-6Mo (called Ti6246) and Udimet 720 nickel based super alloys	Copper wire with CuZn50 coating and copper core with a double layer zinc rich (60% wt.) outer coating	Voltage (V): 80-120, Ignition current (Amp): 4-10, On time (μs): 0.05-0.6, Off time (μs): 0.6-6, Flushing pressure (bar): 1-16, Wire speed (m/min): 10-12, Wire tension (daN): 1.2-2.0, Wire offset (mm): 0.135-0.160.
Sen et al., (2012) [22]	EDM	Ti-6Al-4V-*x*B (with x = 0.0, 0.04, 0.09)	Copper	Voltage (V): 80-120, Capacitance : 100-400 nF
Gu et al., (2012) [24]	EDM	Ti-6Al-4V alloys	Copper	Tool polarity: positive, Open voltage (V): 120, Pulse, T_{on}/T_{off} (μs): 24/100, Flow rate (L/min) 1-4, Peak Current (A): 76-127, Pulse Duration, T_{on} (μs): 8-40.
Weingartner et al., (2012) [81]	WEDM	Brass	Zinc-coated brass	Discharge duration (μs): 1.15-1.20, Peak current (A): 58-73, Pause interval time (μs): 400, Relative speed (m/s): 0.5-80, Oil flow rate (L/min): 25, Blasogrind HC5 oil.

Table 3. Techniques used for correlation.

Authors	Process	Techniques used
Tarng et al., (1994)[82]	WEDM	Neural network applied to determine the optimal cutting parameters
Liao et al., (1997)[47]	WEDM	Proposed the optimal WED-Machining parameters based on the Taguchi design and mathematical models.
Speddingetal., (1997)[83]	WEDM	Attempted to optimization of process parameters using artificial neural network
Banerjee et al., (1997)[54]	WEDM	Analyzed the debris movement in dielectric flow using CFD
Lambert et al., (2002)[84]	EDM	Proposed the modal convection to wire stability.
Guo et al., (2003)[85]	WEDM	Studied the vibration of the electrode using computer simulation and mathematical modeling
Wang et al., (2003)[86]	EDM	Hybrid artificial neural network and genetic algorithm to optimize the process parameters.
Ghanem et al., (2003)[55]	EDM	Experimental and Finite element model to assess the residual stress
Das et al., (2003)[87]	EDM	Finite element simulation based calculation for residual stress and deformation
Tosun et al., (2003)[88]	WEDM	Studied the performance effect of parameters using experimental design method
Liao et al., (2004)[75]	WEDM	Analyzed the surface roughness using the Taguchi quality design
Sanchez et al., (2004)[48]	WEDM	Accuracy of corner cutting corner is improved by the numerical simulation
Saha et al., (2004)[89]	WEDM	Finite element modeling for optimization and prevention of wire breakage
Sarkar et al., (2005)[76]	WEDM	Artificial neural network is developed to model the machining process
Chiang et al., (2006)[90]	WEDM	Grey relational analysis is applied to analyse the multiple machining performance characteristics
Bhattacharyya et al., (2006)[91]	EDM	Taguchi and Gauss elimination method is used to optimize the WEDM parameters
Ramakrishnan et al., (2006)[92]	WEDM	The Tagichi's robust design approach is proposed to WEDM operations
Sarkar et al., (2006)[66]	WEDM	Developed suitable machining strategy for a maximizing WEDM response
Kanlayasiri et al., (2007)[93]	WEDM	2^K factorial design is used to study the influence of parameters on the surface roughness
Yan et al., (2007)[68]	WEDM	Developed a Transistor controlled RC type fine finish power supply for WEDM to achieve fine surface finish.
Mahapatra et al., (2007)[94]	WEDM	Genetic algorithm is applied to optimize the MRR, surface roughness and cutting width
Bhattacharyya et al., (2007)[49]	EDM	A mathematical model is developed based on the Response surface methodology
Han et al., (2007)[95]	WEDM	Thermal analysis is carried out using FEM
Assarzadeh et al., (2008)[96]	EDM	For achieving maximum MRR and optimum Ra proposed a neural network based modeling.
Yan et al., (2008)[97]	WEDM	Genetic Algorithm based fuzzy logic controller for the closed loop wire tension control system
Ali et al., (2008)[50]	WEDM	A statistical model was established to high surface finish using DOE
Mohammadi et al., (2008)[98]	WEDM (Turning)	L_{18} orthogonal array is used and analysis of signal to noise ratio was applied to obtain optimum machining combination parameters
Haddad et al., (2008)[99]	WEDM (Turning), CWEDT	Studied the MRR in Wire electric discharge turning using the response surface methodology
Dodun et al., (2009)[51]	WEDM	Generated a mathematical model to evaluate the loss of height and corner contour angle.

Haddad et al., (2009)[100]	CWEDT	Determined the influence of machining performance using DOE
Caydas et al., (2009)[62]	WEDM	The wire tension and feed movement controlled by the genetic algorithm based fuzzy logic.
Okada et al. (2009)[101]	WEDM	Debris motion in flow field was analyzed by computational fluid dynamics analysis
Bhaduri et al., (2009)[78]	EDM	Explored the effect of process parameter combination using L_9 orthogonal array
Poros et al., (2009)[52]	WEDM	Dimensional analysis used to create a Semi empirical model of the efficiency of EDM
Liao et al., (2009)[59]	WEDM	Developed a online analysis system to investigate the ignition delay time in WEDM process.
Gauri et al., (2009)[102]	WEDM	Multi-response optimization procedure using principal component analysis
Taweel et al., (2009)[103]	EDM	Analysis of machining characteristics can be made by central composite rotatable design (RSM)
Sohani et al., (2009)[53]	EDM	RSM based mathematical models of MRR and TWR are developed
Kao et al., (2010)[13]	WEDM	Taguchi and grey relation method was applied to study multiple machining performance characteristics.
Jangra et al., (2010)[104]	WEDM	Predicted the surface roughness and white layer thickness in WEDM using the adaptive Neuro fuzzy interference system based full factorial design experimentation
Chen et al., (2010)[105]	WEDM	Back propagation neural network (BPNN) and simulated annealing algorithm (SAA)
Govindanet al., (2010)[106]	EDM (Drilling)	Taguchi L27 orthogonal array is used to study the main response variables MRR and TWR
Patel et al., (2010)[107]	EDM	Grey relational analysis, Multiple response characteristic optimization
Liu et al., (2010)[108]	EDM (Drilling)	Quadratic model of RSM along with the sequential approximation optimization method
Rahman et al., (2010)[35]	EDM	Investigated the effect of parameters on the MRR using DOE
Haddad et al., (2010)[109]	WEDM, CWEDT	Mixed full factorial design applied to evaluate the responses
Sarkar et al., (2010)[71]	WEDM	The Bayesian ANN model is applied
Joshi et al., (2010)[110]	Die sinking EDM	Process modeling using finite element method has been integrated with artificial neural networks (ANN) and genetic algorithm (GA).
Janaradhan and Samuel (2010)[60]	WEDT	Analysed the effect of machining parameters on MRR, Surface roughness and roundness, using the pulse train data acquried with a acquisition system.
Patowari et al., (2011)[111]	EDM	A Taguchi based DOE technique utilized
Cheng et al., (2011)[80]	EDM	Numerical simulation of Titanium alloy machining in the EDM process using ANSYS software (Thermal model)
Khan et al., (2011)[74]	EDM	Multilayer perceptron with 3 hidden layer feed forward neural networks
Izquierdo et al., (2011)[57]	EDM	Developed thermal model for the prediction of recast layer and residual stress.
Sarkar et al., (2011)[112]	WEDM	To determine the gap force and the wire deflection analytical model is developed
Sanchez et al., (2011)[48]	EDM	Inversion models based on the least Square theory, RSM and ANOVA
Gauri et al., (2011)[113]	WEDM	Grey relational analysis, MRSN ratio, WSN ratio, VIKOR method
Gu et al.,(2012)[24]	EDM	The main and interaction effect of parameters on the responses was studied by the Box-Behnken statistical design
Mukherjee et al., (2012)[114]	EDM	Genetic algorithm, Particle swarm optimization, Sheep flag algorithm, Ant colony optimization, Artificial bee colony algorithm, Bio-geography based algorithm.
Hashim et al., (2012)[115]	EDM	Particle swarm optimization algorithm applied to optimization of controller for EDM mechanism parameters.

method for the multiple responses [47]. To predict the output responses such as MRR, TWR and surface roughness using the Taguchi based, response surface method and full factorial design based regression mathematical models are developed. The surface integrity aspects of WEDM process were analyzed by Bhattacharyya et al. [49] using the response surface methodology.

Moreover the researchers used the some of the techniques to optimize and predict the MRR, EW, surface roughness and cutting velocity in EDM and WEDM are reported in Table 3. As referred from Table 3, finite element method based simulation yields necessary results without doing a number of experiments. The authors were used to analyze and predict the recast layer, temperature distribution and residual stresses appeared in the EDM/WEDMed surface. The finite element model is also used to prevent the wire breakage [56]. The surface roughness, white layer thickness in the WEDM was predicted using adoptive Neuro fuzzy interference based full factorial design experimentation [62].

Some of the researchers [63] have studied the online process analysis and power supply circuit for WEDM to achieve a better surface finish. Apart from this investigation, few researchers have studied the thermal analysis using FEM and developed mathematical models to predict the responses. The researchers keenly utilized the techniques to optimize the process parameters with respect to an output response.

In Table 3, various tools and techniques utilized by researchers for optimization and correlating with the experimental results have been presented. Some of the researchers have studied the online process analysis and power supply circuit for WEDM to achieve a better surface finish. Apart from this investigation, few researchers have studied the thermal analysis using FEM and developed mathematical models to predict the responses. The researchers keenly utilize the techniques to optimize the process parameters with respect to an output response. The review of the literature presented in Table 3 reveals that there is scope to apply newly developed techniques to correlate experimental results with utilization of optimization techniques such as particle swarm optimization (PSO), advanced PSO, computational system for the process design, artificial bee colony technique (ABC), tabu search, hybrid methods, mixed orthogonal array, modeling and simulation packages (Deform 3D), Simulated annealing, cloud computing and teaching learning based optimization (TLBO algorithm).

5. SUMMARY

The researchers represented the surface roughness, surface topography, phase changes, recast layers and residual stress in EDM and WEDM of titanium alloys. From this peer review, there is a need to study the effect of parameters in WEDM of Ti and TiNi based alloys on surface roughness, recast layer, topographical aspects and residual stresses on the machined surface.

From the review of tools and techniques for analysis and optimization of process parameters in EDM and WEDM there is still research gap. The optimization of WEDM process parameters on machining Ti based alloys in terms of response parameters such as MRR, EWR, surface roughness and surface integrity aspects.

The consolidated contributions of the earlier researchers have been segregated and presented in Tables 1, 2, and 3. Table 1 depicts the contribution of researchers on the titanium based material machining using the EDM and WEDM. The researchers have interestingly studied and presented their investigation on the important aspects of machined properties of advanced materials affected by the input parameters and other constituents. It is also clear that, most of the researchers are concentrating on machining of Ti based alloys because of aerospace applications. However, few researchers have worked on the machining of TiNi based alloys using WEDM.

Based on the literature survey, it can be inferred that, the application of WEDM machining has been explored in many fields. However, there is scope for exploring the possibilities of applying WEDM process on Ti based materials. In this regard, the future study shall be extended to explore the machinability aspect of Ti based materials. The Ti based alloys with required mechanical properties for biomedical, mould and die making applications can be precisely manufactured by WEDM and it proved their versatility in miniaturization of components.

6. CONCLUSION

In this paper, an exhaustive literature review of the papers reported by researchers on EDM, WEDM of advanced materials and its parameters has been presented. The study of these papers has indicated that, researchers have used titanium based materials of various kinds of alloys. There are inadequate data on the subsurface alterations occurred during the WEDMing of Ti based alloys. The various tools and techniques utilized by the researchers for correlating the experimental results have been presented. The applications of the products produced by EDM and WEDM have also been presented. Besides the presentation of the contributions of these researches, this paper has evolved the research gaps. One of the research gaps is in the application of EDM and WEDM in TiNi based alloys. The researchers have used some of the well-established tool's techniques for correlating the experimental results. On the other side, various tool's techniques are being evolved by contemporary researchers. In this context, some of the advanced tool's techniques such as ANN, fuzzy logic, PSO, Tabu enhanced GA has not been utilized for correlating experimental results. The literature survey reported in this paper had also revealed that, researchers are concentrating on the experimental parameters such as pulse duration, discharge current, voltage and so on. However, the study of surface integrity of the advanced materials has not been investigated by many researchers. In this background, the research gaps identified in this paper indicate that, there is a scope for contemporary researchers for investigation. Apart from these research gaps, the paper also provides the direction for future research. Some are, there is inadequate data on the machining of TiNi based alloys, other parameters affecting the responses, MRR surface roughness and subsurface alterations generated in WEDMed surface. Further, the study of the effect of parameters on machining of TiNi based alloys with major concentration on the electrical and non electrical parameters such as pulse duration, peak current, discharge voltage, polarity, pulse waveform, dielectric fluid concentration, additives, wire material, wire diameter, wire tension, wire speed, and table feed on the machined surface is another thrust field. This paper has presented significant contributions of the researches on EDM and WEDM on advanced materials. The study of this paper reveals the research gaps, which may be useful for carrying out research by contemporary researchers.

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