Silicon (2019) 11:187–196
https://doi.org/10.1007/s12633-018-9844-x

ORIGINAL PAPER

Effect of Electrode Materials on Different EDM Aspects of Titanium Alloy

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Received: 8 November 2017 / Accepted: 27 March 2018 / Published online: 21 April 2018

Abstract

Electro discharge machining (EDM) is extensively used in modern manufacturing industry because of its advantage over conventional machining method. Titanium alloys are the materials of research concern now for their extensive use in airframes and jet engines. Therefore, dimensional accuracy and surface integrity are the crucial concern for EDMed titanium alloys. The purpose of this study is to investigate the effect of process parameters and different type of electrodes on dimensional accuracy and surface integrity of EDMed Ti-5Al-2.5Sn titanium alloy. In this investigation, a comparative study has been conducted on the EDM performance of Ti-5Al-2.5Sn titanium alloy using different type of electrodes viz. copper, brass and zinc. The process performance has been measured by means of surface roughness (R_a), surface crack density (SCD), radial overcut (ROC) and recast layer. The outcome of using pulse on time, gap voltage, duty cycle, peak current as process parameters on the responses have been studied. Microstructural analysis has been carried out for the machined surfaces for different type of electrodes. Copper electrode provides a good surface finish and least radial overcut followed by brass and zinc electrodes. Thinner and uniform recast layer and higher surface crack density has been found on the EDMed surface machined by copper electrode compared to brass and zinc electrodes. Therefore, copper tool is recommended where higher precision and higher degree of surface finish is required for EDMed product.

Keywords Electro discharge machining · Radial overcut · Recast layer · Surface crack density · Surface roughness · Titanium alloy

1 Introduction

Ti-5Al-2.5Sn is a grade 6 titanium alloy mostly applied in jet engine and air frames owing to its stability at elevated temperatures, superior strength and weldability. It is also used for the manufacturing of steam turbine blades, aircraft engines, high pressure cryogenic vessels, welded stator assemblies and compressor blades, etc. Regardless of its numerous applications, it's not an easy job to machine titanium alloy using conventional machining process [1]. Nevertheless, the non-conventional machining process viz. electro discharge machining process can effectively machine titanium alloy.

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Electro discharge machining is advancement of nonconventional machining process which can machine any electrically conductive materials irrespective of their hardness. Material is removed from the material by means of series of repetitive sparks occurs between the electrode and workpiece [2]. Hascalik and Caydas [3] reported the effect of control parameters and different type of electrode material (copper, graphite and aluminum) on tool wear rate (TWR), material removal rate (MRR) and surface integrity during EDM of Ti-6Al-4V titanium alloy. Wang et al. [4] examined the micro EDM performance of AISI 304 stainless steel and porous stainless steel (PSS) by means of MRR and relative TWR. They reported that better machining efficiency was observed for PSS than the AISI 304. Later on, they performed a comparative study by introducing helical tungsten carbide electrode during micro EDM of Ti-6Al-4V titanium alloy. They reported that helical electrode acquires better machining efficiency by means of higher MRR, low relative TWR and low overcut compared to conventional cylindrical electrode [5]. Khan et al. [6] studied the surface characteristics of EDMed Ti-5Al-2.5Sn using graphite, copper and copper-tungsten electrodes. They reported that copper tungsten electrode yields the better surface quality, whereas the graphite gives worst surface quality at lower discharge energy. Batish et al. [7] explored the effect of electrode materials (graphite, tungsten-copper and brass) on the machining characteristics of die steels (H11, HCHCr and AISI 1045). They reported that higher overcut was achieved by tungsten-copper electrode followed by graphite and brass electrode.

Choudhary et al. [8] examined the effect of copper, brass and graphite electrodes on EDMed stainless steel 316 for studying surface roughness (SR) and MRR. They reported that brass provides a better surface quality than copper electrode. Torres et al. [9] performed an experiment for studying the influence of EDM on Inconel 600 alloy with copper electrodes. They reported that the higher surface quality achieved during negative polarity. Dewangan et al. [10] studied the effect of process parameters and different tool materials (brass, copper and graphite) on the surface integrity viz. surface roughness, white layer thickness and surface cracks of EDMed AISI P20 tool steel. They reported that brass electrode provides better surface integrity followed by copper and graphite electrodes. Dwivedi and Choudhury [11] investigated the consequence of electrode rotation on the surface integrity of EDMed AISI D3 steel and reported that average surface finish enhanced around 9-10% using the rotational tool. Bhaumik and Maity [12] investigated the effect of SiC powder and process parameter on the surface roughness of EDMed AISI 304. They reported that an increase in peak current surface finish deteriorates. Later on they investigated the effect of process parameters and cryotreated electrode on radial overcut and found a significant improvement on dimensional accuracy using cryotreated electrode [13]. Kumar et al. [14] carried out the effect of cryotreatment on the machining performance of Ti-5Al-2.5Sn titanium alloy and showed that surface finish enhanced by 19.58% for deep cryogenically treated alloy as compared to the untreated alloy. Payal et al. [15] performed process modeling by means of MRR and surface roughness during EDM of Inconel 825 using artificial neural network (ANN). Jeykrishnan et al. [16] studied the influence of process parameters on SR of Inconel 825 during EDM process. Puri and Gohil [17] carried out the influence of machining parameters during EDM of Ti-6Al-4V alloy. They found that pulse on time and peak current have the most considerable effect on MRR.

Literature review reveals that a number of studies have been conducted on the EDM performance using different type of electrodes. But no such study has been reported in the EDM process considering Ti-5Al-2.5Sn titanium alloy as workpiece and brass and zinc as electrode material. In this study, experimental investigation has been performed to study the radial overcut (ROC) and surface integrity by means of surface crack density (SCD), surface roughness (R_a) and recast layer thickness of EDMed Ti-5Al-2.5Sn titanium alloy considering gap voltage, peak current, duty cycle and pulse on time as process parameters. Different type of electrodes viz. brass, zinc and copper are considered for this investigation. Microstructural analysis has been carried out after machining using three types of electrode.

2 Materials and Methods

The investigation was carried out in ELECTRONICA-ELECTRAPLUS PS 50 ZNC (die-sinking type) EDM machine. The EDM operation of Ti-5Al-2.5Sn titanium alloy was performed using cylindrical brass, copper and zinc electrodes having 10 mm diameter. Table 1 shows the chemical composition of titanium alloy and Table 2 shows the properties of the workpiece and electrode materials. The machining parameters considered in the study are duty cycle, gap voltage, pulse on time and peak current. The output parameters considered are surface crack density (SCD), radial overcut (ROC), surface roughness (R_a) and recast layer. The process parameters and their levels are given in Table 3.

The effect of electrode materials and process parameters (duty cycle, gap voltage, pulse on time and peak current) was studied during EDM operation. For the investigation both the workpiece and electrode were immersed in EDM oil in the machining tank. Side flushing of 0.5 kgf/cm^2 was used for machining. Each machining was carried out for 10 minutes. Responses viz. ROC and R_a,SCD, recast layer of the machined craters are calculated using these formulas:

Radial overcut (ROC) is the deviation between the diameter of the electrode and machined cavity. The diameter of the electrode and workpiece cavity is measured by the Tool Makers Microscope (Make: Carl Zeiss, Germany).

$$Radial\ Overcut\ (ROC) = \frac{D_h - D_t}{2} \tag{1}$$

where, D_h and D_t are diameters of machined hole and tool

Surface roughness (R_a) is measured in the transverse direction on the machined surface. The process is repeated for three times and the average of three readings is noted

Table 1 Chemical composition of Ti-5Al-2.5Sn titanium alloy

Element	C	Fe	N	O	Al	Sn	H	Ti
%	0.02	0.16	0.02	0.012	5.1	2.6	0.009	Balance

Table 2 Properties of workpiece and electrodes

	Properties		
	Density (g/cm^3)	Melting temperature (^{0}C)	Thermal conductivity (W/m.k.)
Ti-5Al-2.5Sn Titanium alloy	4.41	1570	7.7
Copper	8.96	1084	401
Brass	8.73	930	159
Zinc	7.14	693	116

as roughness value. The surface roughness is measured by Talysurf (Make: Taylor Hobson, Model: Surtronic 3$^+$).

$$Surface\ Roughness\ (R_a) = \frac{1}{L}\int_0^L |y(x)|\,dx \quad (2)$$

where L is sampling length, y is height of peaks and valleys of roughness profile and x is the direction of profile.

Surface crack density (SCD) is measured by the total crack length per unit area. The density of surface cracks was appraised using scanning electron microscopy (SEM) images using a system (Make: JEOL, Japan; Model: JSM-6480). The EDMed surface is observed from the top under SEM at 500X. For getting the SCD the total crack length is divided by the micrograph area (12000 μm^2).

$$Surface\ Crack\ Density(SCD) = \frac{l_1 + l_2 + l_3}{Area} \quad (3)$$

where, l_1, l_2 and l_3 are length of cracks

Recast layer is an inherent feature in EDM process. For revealing the recast layer the cross section of machined samples was polished using SiC emery papers with a grain size of 220, 320, 600, 800, 1000, 1200 and 1500 respectively. Subsequently, the surface was polished with diamond paste (Make: HIFIN, India; Grade: 01-0S-47). Further the specimens were etched for 90 seconds using Keller's reagent for revealing the grain boundary. The micrograph of recast layer was taken using SEM.

Table 3 Process parameter and their levels for Ti-5Al-2.5Sn titanium alloy

Process parameters					
Parameter	Symbol	Levels			Unit
		1	2	3	
Peak current	I_p	10	15	20	A
Duty cycle	Γ	60	75	90	%
Pulse on time	T_{on}	100	200	300	µs
Gap voltage	V_g	40	50	60	V
Fixed parameters					
Flushing pressure	F_P	0.5	kgf/cm^2		
Working time	WT	10	min		
Servo sensitivity	SEN	6			
Anti-arc sensitivity	ASEN	5			

3 Results and Discussion

3.1 Influence of Process Parameters on R_a

Surface roughness (R_a) is the most important and frequently used response parameter that affects the manufacturing cost of the products. Figure 1 depicts the influence of machining parameters on R_a.

Surface quality deteriorates with the increase in I_P for all the electrodes. As I_P increases, the discharge energy increases resulting generation of violent sparks and impulsive force. Consequently, deeper and larger craters are formed on the workpiece surface. After sparking debris are not properly washed out from the workpiece surface. The residues are staying behind at the crater edge to form rough surface [3]. Lower I_P produces small and shallow craters, leading to a comparatively smooth surface finish. Spark energy is directly proportional to the T_{on}. Higher value of T_{on} produces a deeper crater and enhances the material removal. Consequently, R_a enhances. Increase in gap voltage, initially roughness increases and then decreases gradually. At higher V_g, spark frequency decreases due to very large inter electrode gap results decline in roughness. R_a increases with increase in duty cycle because of the dominant effect of discharge current which results deeper machining cavity and provides insufficient time to wash out the residues. From the above investigation it is noticed that higher degree of surface finish has been achieved at lower value of peak current (10A), lower value of pulse on time (100µs), higher value of gap voltage (60V) and lower value of duty cycle (60%).

Overall the copper tool exhibits best surface finish followed by brass and zinc electrode. This takes place because the copper tool acquires higher thermal conductivity (401 W/m.k.) than the brass (159 W/m.k.) and zinc (116 W/m.k.) electrode. Owing to high thermal conductivity of copper tool, heat dissipation rate is higher for the tool. So, the discharge energy density will be inferior that causes the development of less concave crater as compared to the

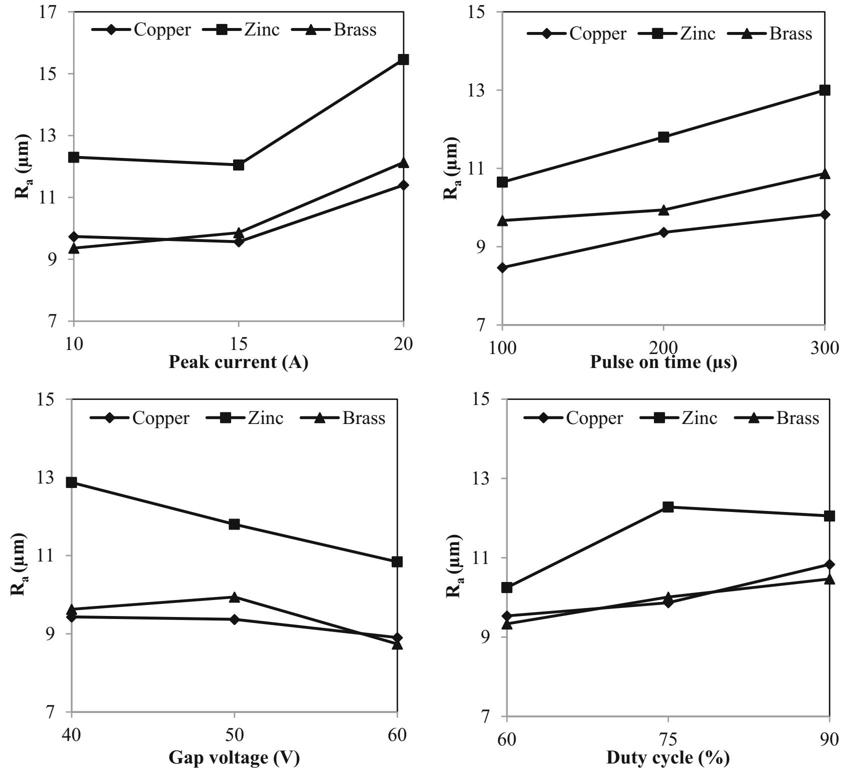


Fig. 1 Effect of I_p, T_{on}, V_g and Γ on R_a

other two electrodes. Apart from this, during cooling time after the washing out of molten metal from the machining gap, residues are falling on the edge of the crater resulting generation of rough surface.

3.2 Influence of Process Parameters on ROC

Radial overcut is an inherent feature in the EDM process which is inevitable, though the suitable compensations are

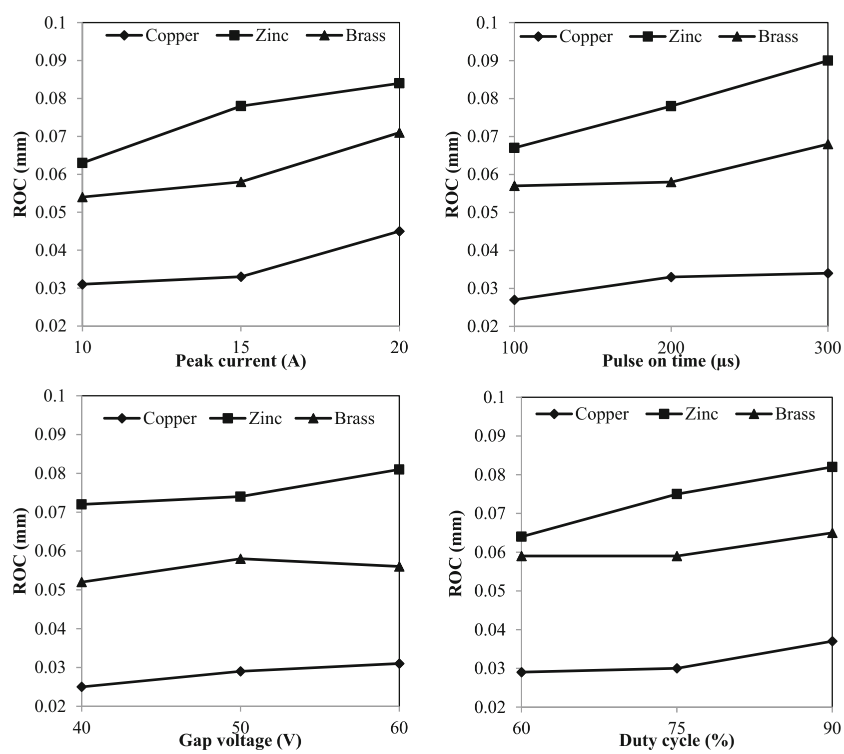


Fig. 2 Effect of I_p, T_{on}, V_g and Γ on ROC

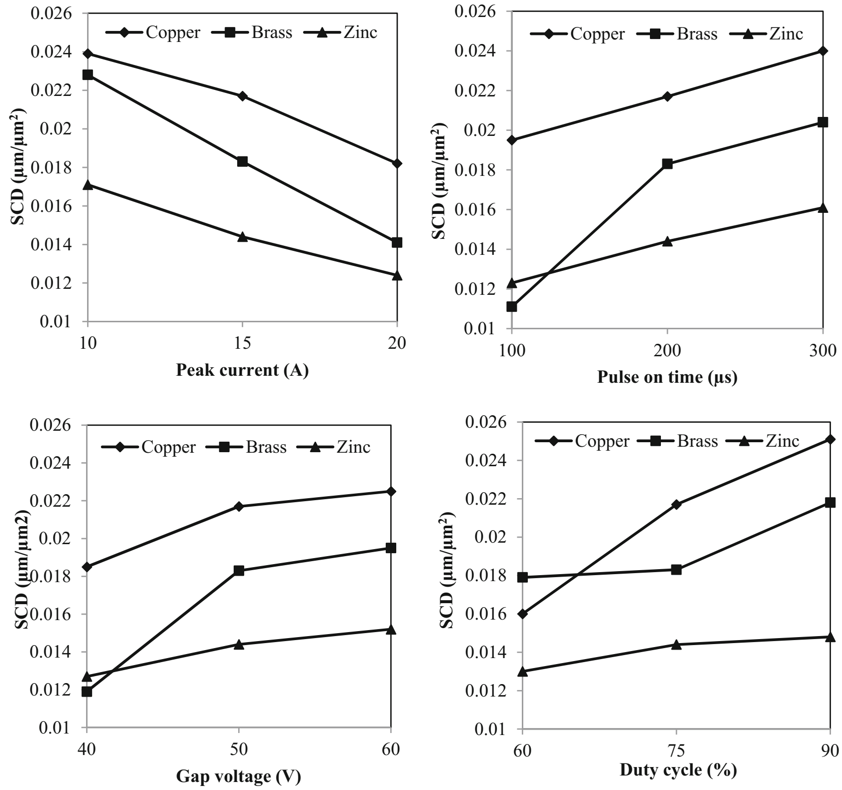
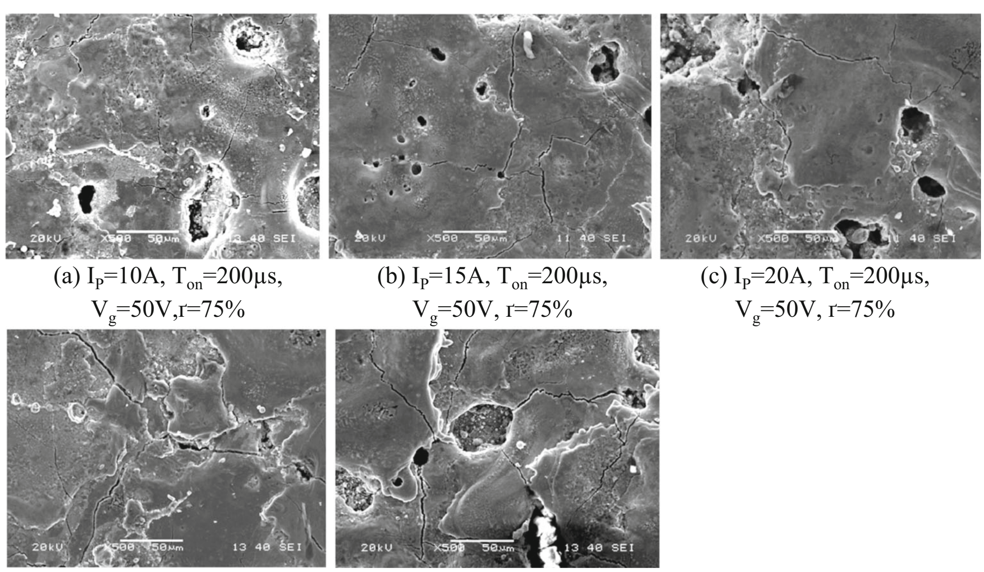


Fig. 3 Effect of I_p, T_{on}, V_g and Γ on SCD

imparted during the tool design. Therefore, to achieve the accuracy the overcut should be kept at least as possible.

Figure 2 depicts the effect of machining parameters on radial overcut. Overcut increases with increase in I_P, T_{on} and τ for the three electrodes. Higher I_P and T_{on} have an unfavorable effect on dimensional accuracy resulting higher overcut. This happens because increase in I_P and T_{on} the discharge energy increases that removes high amount of molten metal from the workpiece resulting higher overcut. With increase in V_g initially overcut increases and then starts falling off for copper and brass electrode. The spark energy increases with increase in V_g leads to increase in MRR hence ROC increases. But at higher V_g, the harsh concentrated discharge would take place. Consequently,



(a) I_P=10A, T_{on}=200µs, V_g=50V,r=75%

(b) I_P=15A, T_{on}=200µs, V_g=50V, r=75%

(c) I_P=20A, T_{on}=200µs, V_g=50V, r=75%

(d) I_P=15A, T_{on}=100µs, V_g=50V, r=75%

(e) I_P=15A, T_{on}=300µs, V_g=50V, r=75%

Fig. 4 SEM images of Ti-5Al-2.5Sn titanium alloy machined by copper electrode at 500X magnification

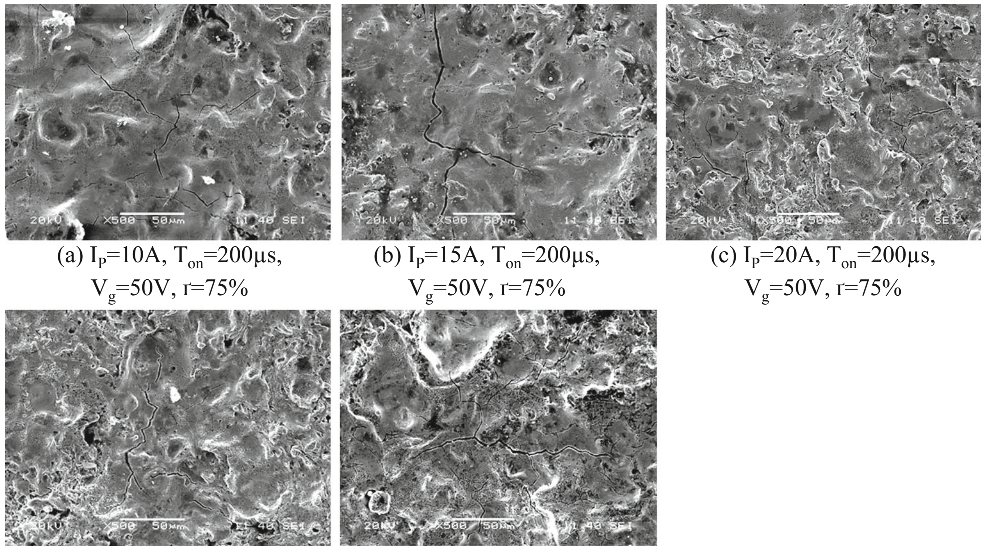


Fig. 5 SEM images of Ti-5Al-2.5Sn titanium alloy machined by brass electrode at 500X magnification

(a) I_P=10A, T_{on}=200µs, V_g=50V, r=75%
(b) I_P=15A, T_{on}=200µs, V_g=50V, r=75%
(c) I_P=20A, T_{on}=200µs, V_g=50V, r=75%
(d) I_P=15A, T_{on}=100µs, V_g=50V, r=75%
(e) I_P=15A, T_{on}=300µs, V_g=50V, r=75%

MRR as well as ROC declines. From the above investigation it is noticed that higher dimensional accuracy has been achieved at lower value of peak current (10A), lower value of pulse on time (100µs), lower value of gap voltage (40V) and lower value of duty cycle (60%).

Overall, the copper tool gives least overcut followed by brass and zinc electrode. The copper tool possesses higher thermal conductivity than the brass and zinc electrode. Due to lower thermal conductivity, the local temperature rises for the zinc electrode. Thus, during sparking the electrode surface faces more melting and vaporization compared to the copper and brass electrode. So the roundness of the zinc electrode gets damaged. As a result, superior dimensional accuracy is achieved for copper electrode owing to uniform sparking and proper maintenance of electrode shape than the other two electrodes.

3.3 Influence of Process Parameters on SCD

Surface cracking is one of the significant surface defects as it causes the deterioration of fatigue resistance and resistance to corrosion of materials especially under tensile conditions. So the surface crack density (SCD) should always be least as much as possible to prevent the fatigue

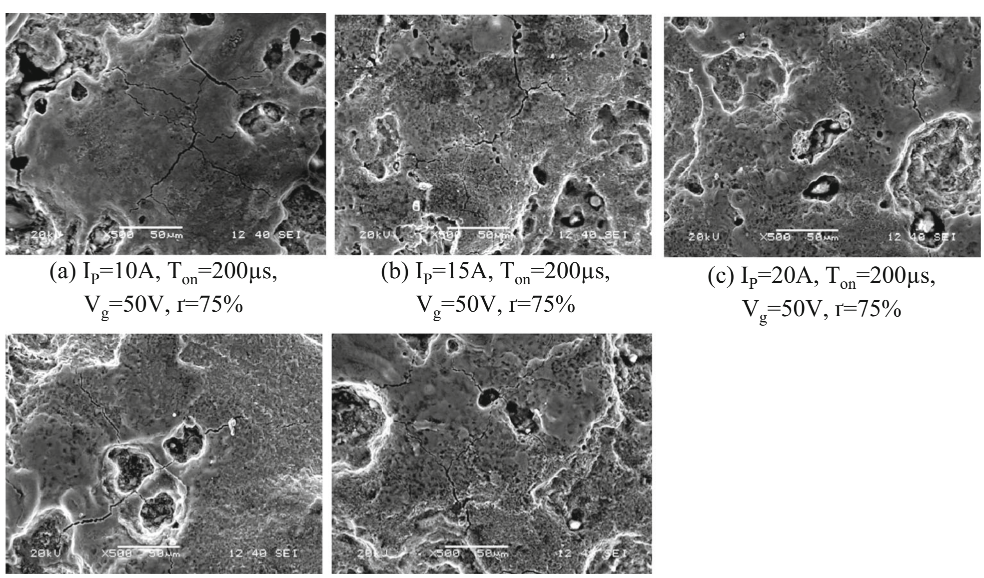
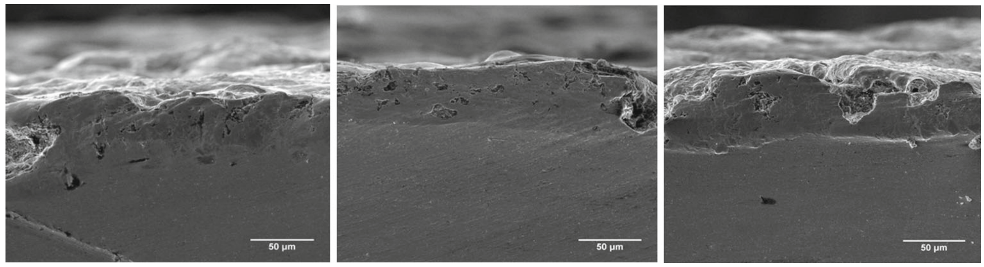


Fig. 6 SEM images of Ti-5Al-2.5Sn titanium alloy machined by zinc electrode at 500X magnification

(a) I_P=10A, T_{on}=200µs, V_g=50V, r=75%
(b) I_P=15A, T_{on}=200µs, V_g=50V, r=75%
(c) I_P=20A, T_{on}=200µs, V_g=50V, r=75%
(d) I_P=15A, T_{on}=100µs, V_g=50V, r=75%
(e) I_P=15A, T_{on}=300µs, V_g=50V, r=75%

Fig. 7 SEM images of recast layer for copper electrode



(a) I_P=10A, T_{on}=200µs, V_g=50V, r=75% (b) I_P=15A, T_{on}=200µs, V_g=50V, r=75% (c) I_P=20A, T_{on}=200µs, V_g=50V, r=75%

strength of the product. Figure 3 depicts the influence of process parameters on SCD. Increase in I_P, SCD decreases steadily. The reduction of SCD is characterized to the fact that as the I_P increases, more amount of material is melted which have a propensity to fill up the voids. So, the probability of crack initiation declines [18]. Increase in T_{on}, the molten metal quantity would be high and during cooling induced thermal stress is developed, resulting increase in SCD. As the discharge energy is directly proportional to V_g, consequently crater size increases with increase in V_g. Accordingly, the surface crack length increases. Increase in duty cycle SCD increases because of lack of heat dissipation to the surrounding. From the above investigation it is noticed that lower density of surface cracks has been achieved at higher value of peak current (20A), lower value of pulse on time (100µs), lower value of gap voltage (40V) and lower value of duty cycle (60%).

The copper electrode possesses higher SCD followed by brass and zinc electrode. This happens because of higher thermal conductivity of copper electrode than the other two electrodes. During T_{on}, the thinner recast layer is formed as less amount of heat is transferred to the workpiece which does not fulfill the cracks properly on the workpiece causing higher SCD.

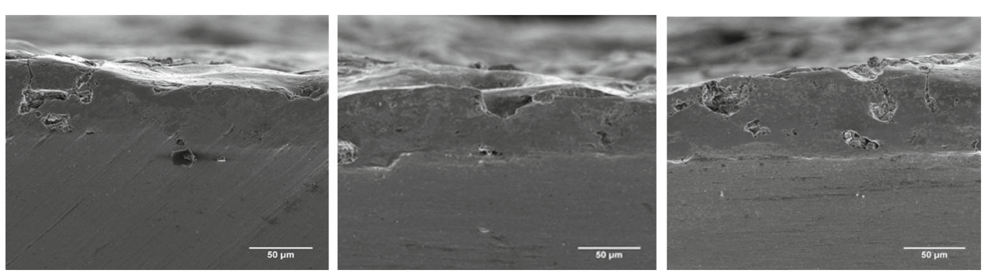
3.4 Microstructural Analysis

The surface topography of EDMed Ti-5Al-2.5Sn titanium alloy is investigated using SEM at 500X magnification. Figures 4, 5 and 6 represent the EDMed surface using copper, brass and zinc electrode respectively. The EDMed surface consists of globules, pock marks, craters and surface cracks. Consequently, the machined surface has an uneven surface texture.

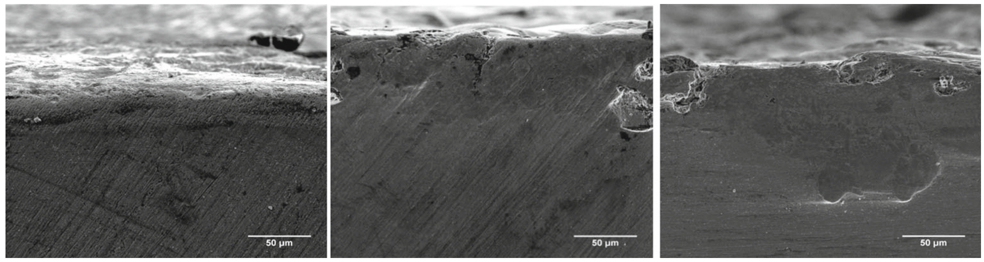
The surface is characterized by crater, pock marks, surface cracks and globules of debris. Figures 4a-c, 5a-c and 6a-c depict the surface topography with different value of I_P. The superiority surface texture getting deteriorates with increase in I_P. High I_P corresponds to higher MRR that results deep craters. Cracks are generated on the machined surface because after T_{on} the machined surface is rapidly cooling down by the dielectric fluid during pulse off time resulting developing residual tensile stress. Hence, crack formation initiated [19]. It is evident that, the number of cracks lessens as the I_P increases, but the crack width becomes wider with increase in I_P. The residue of molten material re-solidified on the machined surface after rapid cooling and forms globules of debris. The number of globules seems to be lesser as the I_P increases. When I_P increases, the similar trend was observed for pock marks. Figures 4d-e, 5d-e and 6d-e depict that increase in T_{on} the surface texture becomes more rutted. Crater size increases with increase in T_{on}. This happens because increase in T_{on} discharge energy increases, causing melting and vaporization of workpiece. The presence of globules decreases as the T_{on} increases. Degree of pock marks is apparent at lower value of T_{on} compared to higher value of T_{on}.

It is apparent from all the figures that the zinc electrode produces larger crater size than the other two electrodes. The higher degree of surface cracks are observed for copper

Fig. 8 SEM images of recast layer for brass electrode



(a) I_P=10A, T_{on}=200µs, V_g=50V, r=75% (b) I_P=15A, T_{on}=200µs, V_g=50V, r=75% (c) I_P=20A, T_{on}=200µs, V_g=50V, r=75%



(a) I_P=10A, T_{on}=200µs, V_g=50V, r=75% (b) I_P=15A, T_{on}=200µs, V_g=50V, r=75% (c) I_P=20A, T_{on}=200µs, V_g=50V, r=75%

Fig. 9 SEM images of recast layer for zinc electrode

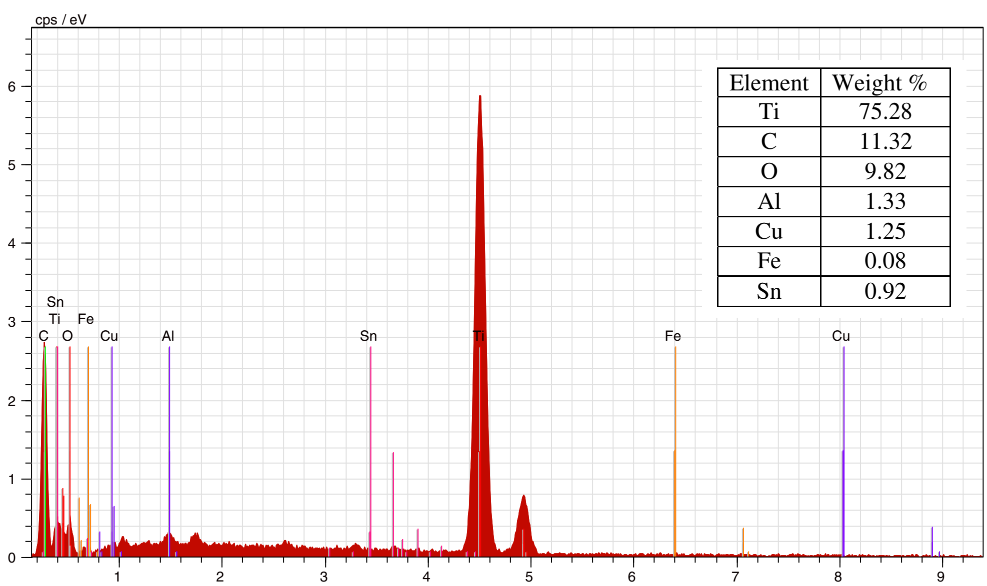
electrode compared to brass and zinc electrode. The copper electrode produces finest surface structure whereas the zinc electrode produces worst surface structure. From the analysis it is understood that the density, melting point and thermal conductivity of electrode notably affect the tool wear with surface topography [6]. The copper tool produces superior surface structure because of its higher thermal conductivity, higher density and higher melting temperature.

3.5 Recast Layer

During the EDM process, the spot temperature reaches to about 10,000 °C. At this temperature, material on the spot melts and vaporizes from the workpiece. During this process some molten material stays on the workpiece and subsequently resolidifies during cooling to develop a recast layer. During sparking the very high thermal energy modifies the microstructure of sub-surface region to a certain depth called heat affected zone (HAZ). Beyond the heat affected zone the bulk material exists which remain unaffected by the EDM process.

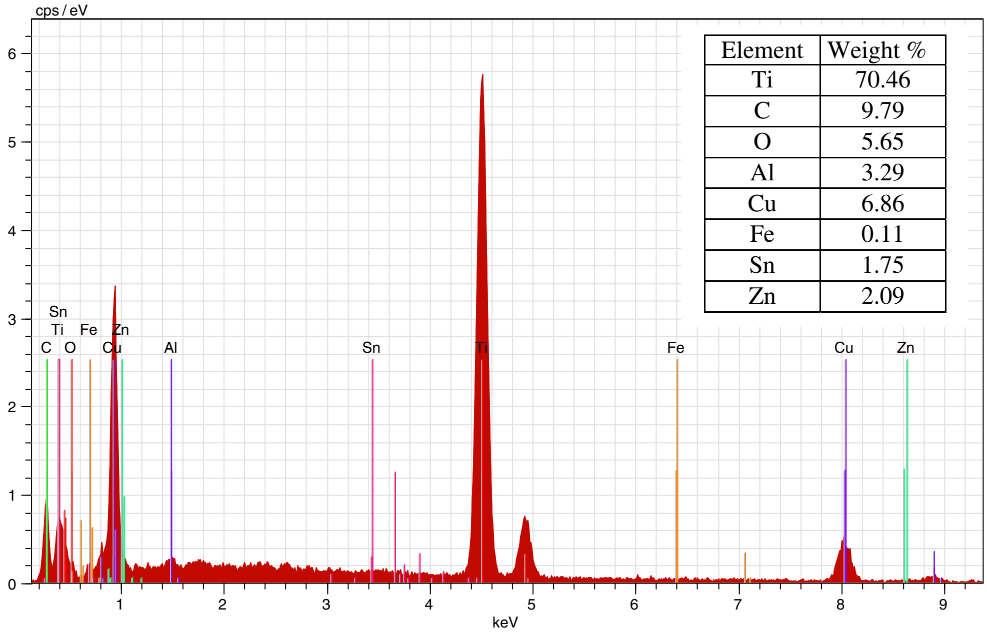
Figures 7, 8 and 9 show the recast layer for copper, brass and zinc electrode respectively at different level of peak current 10A, 15A and 20A. It is observed that increase in peak current recast layer thickness increases because discharge energy directly proportional to the peak current. Increase in peak current volume of molten material would be higher. Owing to improper flushing it could not be flushed away properly resulting generation of recast layer. Ramasawmy et al. [20] also reported that increase in discharge energy white layer thickness increases. The recast layer appeared to be thinner for copper electrode compared to brass and zinc electrode owing to its higher thermal conductivity. Recast layer formed by copper electrode is uniform by nature, whereas the recast layer formed by zinc electrode is non-uniform.

Energy-dispersive X-ray spectrometry (EDS) analysis has been performed to investigate the chemical composition of recast layer after EDM operation of titanium alloy by



Element	Weight %
Ti	75.28
C	11.32
O	9.82
Al	1.33
Cu	1.25
Fe	0.08
Sn	0.92

Fig. 10 EDS analysis of EDMed surface at I_P =15A, T_{on} =200µs, V_g=50V, Γ=75% machined by copper electrode



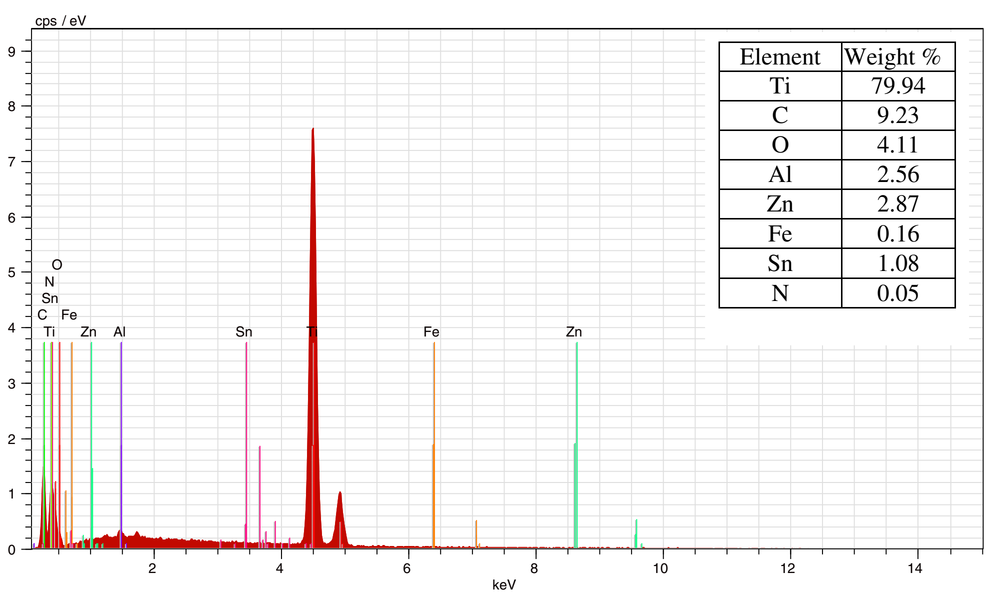
Element	Weight %
Ti	70.46
C	9.79
O	5.65
Al	3.29
Cu	6.86
Fe	0.11
Sn	1.75
Zn	2.09

Fig. 11 EDS analysis of EDMed surface at I_P =15A, T_{on} =200µs, V_g=50V, Γ=75% machined by brass electrode

copper, brass and zinc electrode. From Figs. 10, 11 and 12 the maximum peak height of titanium (Ti) are clearly visible in the EDS spectra. After EDM operation 11.32, 9.79 and 9.23 wt% carbon content are found on the machined surface. The higher amount of carbon content has been found out because of decomposition of dielectric fluid at high temperature resulting deposition of carbon on the machined surface as reported by Hascalik and Caydas (2007). The residues of electrodes are also found out in the recast layer. This may happen owing to the material migration during EDM operation due to melting and re-solidification of electrode material.

4 Conclusions

In this investigation, a comparative study has been conducted on EDM of titanium grade 6 alloy using different type of electrodes viz. copper, brass and zinc. The following conclusions have been drawn from the work:



Element	Weight %
Ti	79.94
C	9.23
O	4.11
Al	2.56
Zn	2.87
Fe	0.16
Sn	1.08
N	0.05

Fig. 12 EDS analysis of EDMed surface at I_P =15A, T_{on} =200µs, V_g=50V, Γ=75% machined by zinc electrode

1. Copper electrode provides a good surface finish followed by brass and zinc electrodes. At lower value of peak current (10A) and pulse on time (100μs) EDM produces good surface finish machined by copper and brass electrode.
2. Copper tool gives less radial overcut followed by brass and zinc electrode. At lower peak current (10A) brass and zinc electrode exhibits less overcut.
3. The copper electrode produces finest surface structure followed by brass and zinc electrode. The highest degree of surface cracks are observed for copper electrode compared to brass and zinc electrode.
4. From the microstructural analysis, it is found that zinc electrode acquires higher surface defects than copper and brass electrode. Recast layer found to be thicker as the peak current increases. Copper electrode exhibits thinner and uniform recast layer compared to brass and zinc electrode.

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