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RESEARCH

Assessing the Effects of Uncoated and Coated Electrode on Response Variables in Electrical Discharge Machining for Ti-6Al-4V Titanium Alloy

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A B S T R A C T

The coated electrodes with high heat resistant alloy materials can considerably improve the efficiency of electrical discharge machining (EDM) process. In the present study, the influence of Aluminum Chromium Nickel Coated aluminium electrode was investigated on the quality criteria using EDM while machining Titanium alloy (Ti - 6Al-4V). The peak current, gap voltage and pulse-on time were used as input parameters to analyze the material removal rate, tool wear rate and surface roughness under the L16 based Taguchi method and ANOVA method. It was observed that Aluminum Chromium Nickel (AlCrNi) coated electrode could produce higher material removal rate (MRR), lower of tool wear rate (TWR) and surface roughness (Ra) than uncoated electrode. Compared with EDM with uncoated electrodes, the quality indicators in EDM with coated electrode are better, namely 8% higher MRR, the lower TWR and Ra are 8% and 24%, respectively. The better surface finish was also observed with the coated electrode due to its thermal conductivity.

1. INTRODUCTION

Electric discharge machining (EDM) is the thermal erosion method in which the material can be removed by melting or vaporizing the materials from the surface of workpiece. The controlled erosion of the workpiece can be happened by applying repetitive electrical sparks between the work and tool electrode submerged in a dielectric medium [1]. This machining process is extensively employed in the production of complex shape dies and molds tools with higher strength materials such as tungsten carbide, hard alloy steels, hastalloy, nimonic, etc [2]. The better finishing of the components for aeronautical and automobile industries can be machined using EDM method [3].

It was experimentally investigated to analyze the effects of nickel-coated composite electrode and diamond-nickel-coated composite electrode for reducing the side tool wear of the specimens [4]. A process simulation was presented to analyze the residual stress in micro-EDM machining on molybdenum. The pulse duration can highly contributed on the crater dimension and the tool wear percentage [5]. The impact of grain size of the boron-doped CVD diamond coating was investigated on wear behavior in micro EDM process. The CVD diamond coatings could produce tiny discharge craters compared to microcrystalline diamond coatings with melting crystalline phase around the discharge crater [6]. The CNT coated electrodes can improve the higher material removal rate (MRR) and lower tool wear rate (TWR). The surface of the electrode is coated with diamond material by the PCD method in EDM for machining SKD11 and tungsten carbide (G5), and this causes a very sharp decrease in TWR [7]. Compared with uncoated electrodes, the wear of the coated electrode is reduced approximately 20-50 times. EDM using diamond-coated electrodes has resulted in increased electrode wear resistance, this results in a significantly improved machining productivity [8,9]. Survey results of the effects of TiN and TiAlN coating on Cu electrode's wear resistance in EDM showed that TWR of TiN and TiAlN coated Cu electrode has been strongly improved [10]. And compared with the TiAlN coated electrode, the TWR of TiN coated electrode is significantly smaller. TWR in EDM using zinc, silver and hard chrome coated copper electrode is higher than it of uncoated electrode, this is due to the coating material being removed from the substrate electrode's surface layer [11]. The reason is that the thickness of the coating (≈3μm) is too small. The surface roughness (Ra) was also reduced as compared with uncoated tools [12]. The TiC-Cu powder tool electrode was prepared with composite coating on AISI 1020 steel by the electro-discharge coating (EDC) process. The experimental results revealed that the peak current, processing range, and pulse on time had a major effect on the performance of the coating due to alteration in the deposition of the coating material [13]. A novel TiN-Cu electrical discharge machining electrode was proposed and fabricated by gel injection molding with the mixture of TiN-Cu powders, sodium-alginate dispersant and gelatin binder. The influence of the gel properties was investigated on surface microstructures and relative loss-rate of the newly developed EDM electrode to optimize the fabrication conditions [14]. It was found that tool wear was increased with higher voltage and current values [15]. The effect of the titanium carbide (TiC) in sintered copper–tungsten (Cu–W) electrodes on their EDM performance was investigated. The highest relative density and lowest electrical resistivity could be obtained by 15% TiC addition and thus produced lowest TWR, highest MRR and best surface finish [16]. The copper coated aluminum (Al) electrodes could significantly affects the MRR, TWR and Ra in EDM process [17]. The CNT coated electrode and TiN coated electrodes can also increase the efficiency of the EDM process compared to uncoated electrodes [18-20]. The study portrayed the potential of the EDM input parameters for improving the MRR and surface quality of Co-Cr alloy and DSS alloy [21]. Power mixed EDM and its influence on machining performance were studied for various workpiece materials [22-25].

From the detailed experimental investigations, it was inferred that only little attention was provided on analyzing the effects of coated electrodes in EDM process. Specific methodologies like power mixed EDM, dry EDM, ultrasonic EDM etc were used in EDM but thin film coated electrode tools were used in very few experimental work. Aluminum-Chromium-Nickel (AlCrNi) is a very promising coating material for the electrodes in EDM, but no studies have been investigated with this coating material. In addition, aluminum electrodes are also very popularly used in EDM, however the number of studies done with coating aluminum electrode in EDM is very little, and in particular, no studies have been done with the AlCrNi Coated Al electrode in EDM. Hence the present investigation was carried out. In the present study, the influence of Aluminium-Chromium-Nickel (AlCrNi) Coated Al electrode was investigated on the quality criteria using EDM while machining Titanium alloy (Ti - 6Al-4V).

2. EXPERIMENTAL METHODOLOGY

2.1 Selection of workpiece

The titanium alloy (Ti-6Al-4V) was used as workpiece specimens in the present study, since it is mostly utilized in manufacturing industries owing to its higher stregnth, corrosion resistance, lower density better weldability, workability and thermal process ability. The materials were procured from Bharat Aerospace, Mumbai with chemical composition as shown in Table 1. The physical properties of the specimens is given in Table 2.

Table 1. Chemical composition of Ti-6Al-4V.

Element	Al	V	C	Fe	Ti
Wt (%)	5.60	4.50	0.02	0.012	Balance

Table 2. Physical properties of Ti-6Al-4V.

Property	Value
Melting point (° C)	1.649
Density (g/cm3)	4.43
Thermal conductivity (W/m-K)	7.2
Hardness (HRA)	48-49
Electrical resistivity (ohm-cm)	170

2.2 Selection of tool electrodes

The machining experiments were performed in electric discharge machining process using uncoated Al tool electrode and AlCrNi coated tool electrodes. The main aim of experiment is to study the effects of AlCrNi coated tool electrode on machining performances as comparison with uncoated electrodes. The machining experiments have been performed with conventional Al tool electrode and uniformly AlCrNi coated Al electrode with the diameter of 9.95 mm. Coating thickness of TiN was measured by surface rugosity meter avaible at Oerlikon Balzers Coating India Pvt. Ltd., Pune. Average diameter of thin film coated TiN micro tool electrode is 500.00 micron. Schematic of tool electrode is shown on Figure 1.

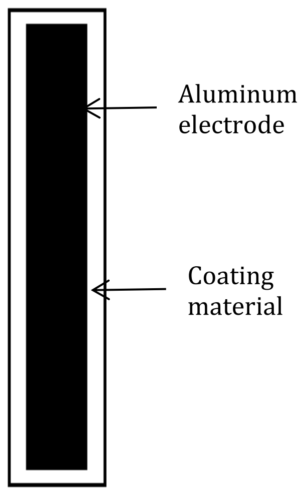


Fig. 1. Schematic diagram of coated tool.

The development of thin film coating of AlCrNi was achieved using physical vapour deposition method (PVD). This uniform coating on tool electrode was conducted in Balzer India Pvt. Ltd, Pune, India. The presence of Al and chromium (Cr) in the coating was characterized by the proposed method.

2.3 Selection of process parameters and variables

The machining experiments have been performed with conventional Aluminum tool electrode and uniformly AlCrNi coated aluminum electrode with the diameter of 10 mm. The experimental investigation was performed to produce higher MRR with lower TWR and surface roughness for improving machining efficiency. The coating enhances the electrical conductivity and better abrasive wear with the compatible dielectric medium. Experimental work were performed on ZNC EDM (Make : Electronica India, Pvt. Ltd, India. Photograph of ZNC EDM is shown in Figure 2.

2.4. Design experimental and ANOVA

Mechanism of EDM processing is unclear due to the large number of technology parameters. Experimental design using Taguchi method is very simple; it is used in many technical fields with high efficiency. The process parameters in the experimental matrix may choose large numbers (3 ÷ 50) with the different possible values. The value of the levels of the research technology parameters is any selected. Especially, studies with new machining methods and unclear mechanism will be very suitable with Taguchi method [33]. The design of an experimental matrix using the Taguchi method through special orthogonal matrices is available. With this method, the number of process parameters included in the empirical matrix and their levels are maximized, but the number of experiments is minimized. The process parameters studied can be qualitative or quantitative, discrete nature of the input variables, interactions between input parameters, etc. These problems cannot be realized in traditional experimental design methods. Compared with the experiments via traditional method, the testing cost of Taguchi method is reduced by 88.9%, and the results of the two methods are the same [34]. In some specific cases, Taguchi method can be used as a substitute for central composite design, Shainin System DoE, Response Surface Methodology (RSM), Full Factorial Design, etc [35-37]. Taguchi technique is normally used in linear interactions only. This is due to the fact that in Taguchi design, interactions between controls factors are aliased with their main effects. Selection of an orthogonal array depends upon the number of factors, and their degrees of freedom (dof) from each factor. The change in the mean of quality characteristics is used to determine the influence of parameters on the research process. Therefore, Taguchi's method can be used to study the technological parameters of EDM process.

For this study the main effects of the input parameters were considered as shown in Table 3. The selection of an orthogonal array depends upon the number of factors and degrees of freedom with each factor. For this study 3 main factors were considered, with 3 main factors had four levels, each having three DOFs, thus, the total sum of DOFs was 9, Table 3. Therefore, L_{16} based OA was chosen for the final experimental investigation.

Fig. 2. Experimental setup (ZNC EDM).

Table 3. Process parameters and levels.

Parameters	Symbol	Levels				DOF
		1	2	3	4	
Peak Current	I	10	20	30	40	3
Gap Voltage	Vg	40	45	50	55	3
Pulse-ON Time	TON	100	500	1000	1500	3
Total						9

2.5 Computation of response parameters

Material removal rate, tool wear rate and surface roughness were considered as performance measures to access the quality in the present study. Material removal rate (MRR) was computed using Eqn 1.

$$\text{MRR (gm/ min)} = \frac{Wi - Wf}{t} \quad (1)$$

Where, Wf and Wi were final weight and initial weight of workpiece before machining and after machining respectively and t is machining time.

Tool wear rate (TWR) was computed using Eqn 2.

$$\text{TWR (gm/min)} = \frac{Ti - Tf}{t} \quad (2)$$

Where, Ti and Tf are initial weight of tool before machining and final weight of tool electrode and t is machining time.

Surface roughness (Ra) of machined workpiece surface was measured by contact type surface roughness tester (Taylor Hobson machine, Surtronic S-100 Series Surface Roughness Tester) with the cutoff length of 0.8mm. Assessment were performed on surface of workpiece machine (four directions; outside to inside). Each surface was assessed four times and then noted average value of surface roughness. Prob tip radius was 5 micro meter and sampling length was 2.5 mm.

3. RESULTS AND DISCUSSION

In the present study, an attempt has been performed to investigate the effect of coated and uncoated electrodes on the material removal rate (MRR), tool wear rate (TWR) and surface roughness (Ra) on machining titanium (Ti-6Al-4V) alloy. The experimental results have been computed and recorded as shown in Table 4.

3.1 Effects on tool coating on material removal rate

Table 5 shows the analysis of variance(ANOVA) for material removal rate with uncoated electrode. It was observed that Current (I) has the major significance on material removal rate due to its importance on determining spark energy in EDM process. It can be stated that the pulse-on time (TON) has also considerable effect, since it could affect duration of spark energy to be delivered.

Figure 3 shows the main effects plots on MRR with uncoated electrodes which has been obtained using Minitab software package. It shows the behavior of process parameters on MRR in EDM process. It is pictorial representation of the ANOVA analysis. It can be seen that the material removal rate increases with increasing with higher pulse time. The deeper discharge craters have been formed under higher pulse time and resulted in higher MRR along with each spark, since the spark energy is directly proportional to the pulse-on time.

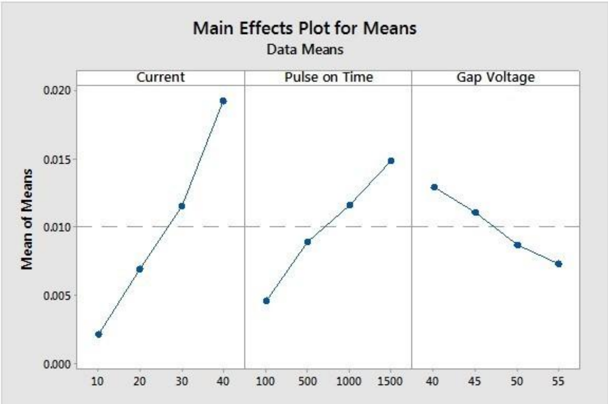


Fig. 3. Main effect plot on MRR using Al electrode.

Table 6 shows the analysis of variance(ANOVA) for material removal rate with coated electrode. The coated electrodes could also produce same effect as that of uncoated tool electrode in EDM process. However after at 500µs, the MRR was also reduced owing to the current required to charge the machining zone. This phenomenon was been observed by few research works[25, 26, 27]. Since the gap voltage has not much contributed during the discharge process, it has very lower influence on producing craters and resulted in less effect on MRR [28,29].

Figure 4 shows the main effects plots on MRR with coated electrodes which has been obtained using Minitab software package. It was observed that peak current has the ability to produce the larger discharge craters and possess higher influence on determining MRR.

While analyzing the consolidated results, if was observed that AlCrNi coated electrodes could improve the 8% higher MRR as compared with uncoated electrode owing to the higher electrical and thermal conductivity of the tool electrode surface of the surface coatings during the machining process as shown in Figure 5.

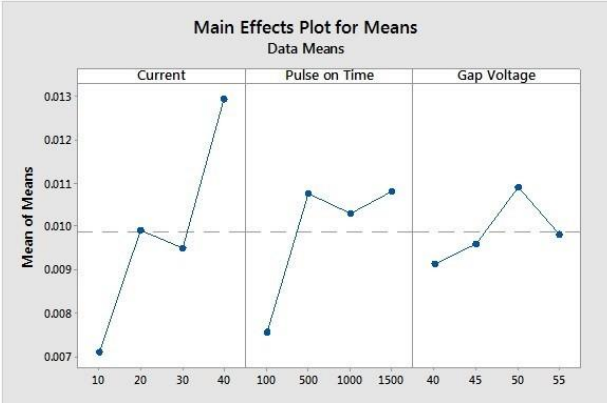


Fig. 4. Main effect plot for MRR using AlCrNi coated electrode.

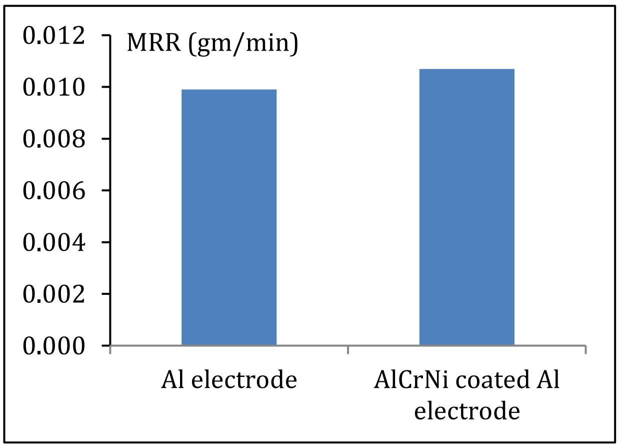


Fig. 5. Comparison of MRR with uncoated and coated electrode.

3.2 Effects on tool coating on Tool wear Rate

Table 7 shows the analysis of variance (ANOVA) for tool wear rate with uncoated electrode. It was observed that Current (I) has the major significance on tool removal rate due to its importance on determining spark energy in EDM process. It can be stated that the pulse-on time (T_{ON}) has also considerable effect, since it could affect duration of spark energy to be delivered [27,28].

Fig. 6 shows the main effects plots on TWR with uncoated electrodes which has been obtained using Minitab software package. It shows the behavior of process parameters on TWR in EDM process. It can be seen that the tool wear rate increases with increasing with higher pulse time. The deeper discharge craters have been formed under higher pulse time and resulted in higher TWR along with each spark, since the spark energy is directly proportional to the pulse-on time.

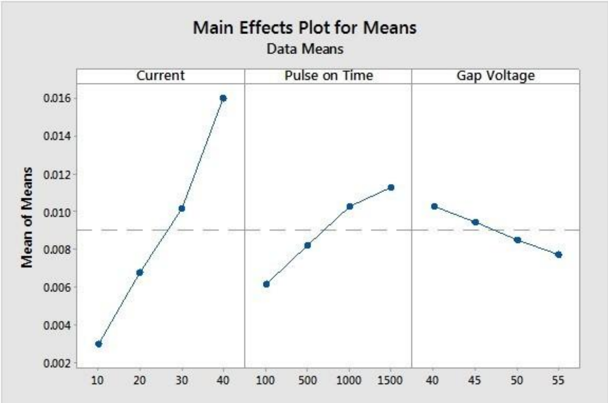


Fig. 6. Main effect plot for TWR using Al electrode.

Table 8 shows the analysis of variance(ANOVA) for tool wear rate with coated electrode. The coated electrodes could also produce same effect as that of uncoated tool electrode in EDM process. However the coating could reduce the effects of creating craters over the tool electrode. Hence it could produce lower tool wear rate compared with uncoated electrode. Fig. 7 shows the main effects plots on TWR with coated electrodes which has been obtained using Minitab software package. It was observed that peak current has the ability to produce the larger discharge craters and possess higher influence on determining TWR.

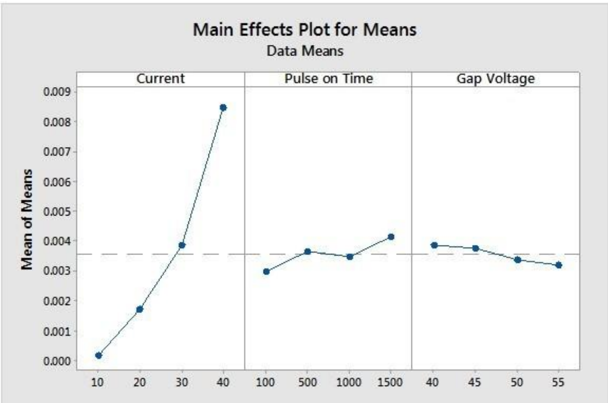


Fig. 7. Main effect plot for TWR using AlCrNi coated electrode.

While analyzing the consolidated results, if was observed that AlCrNi coated electrodes could improve the 24% lower TWR as compared with uncoated electrode owing to the less erosion made by surface coatings during the machining process as shown in Figure 8. Since the AlCrNi is hard coating which has been used to protect tools from wear during machining processes, less reduction in tool wear was observed as compared to uncoated Al electrode.

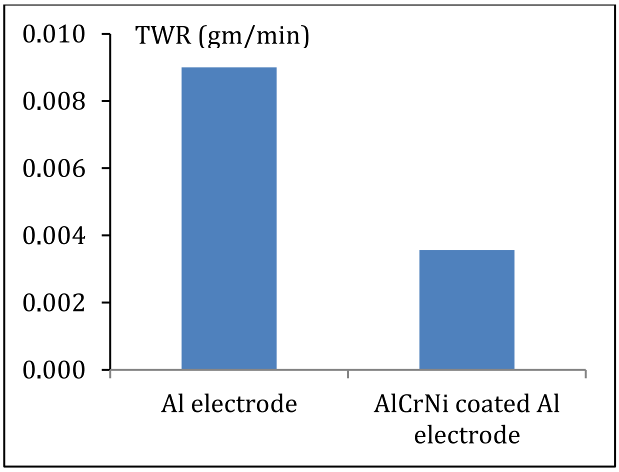


Fig. 8. Comparison of TWR with uncoated and coated electrode

3.3 Effects on tool coating on surface roughness

Table 9 shows the analysis of variance (ANOVA) for surface roughness with uncoated electrode. The surface roughness is generally characterized by the size and the distribution of the craters in EDM process. It was observed that current (I) has the major significance on surface roughness due to its importance on determining crater formation in EDM process [29,30]. It can be stated that the pulse-on time (T_{ON}) has also considerable effect, since it could affect duration of spark energy.

Figure 9 shows the main effects plots on Ra with uncoated electrodes which have been obtained using Minitab software package. It shows the behavior of process parameters on Ra in EDM process. It can be seen that the surface roughness increases with crater size. The deeper and larger discharge craters have been formed under higher pulse time and resulted in higher Ra along with each spark, since the spark energy is directly proportional to the pulse-on time.

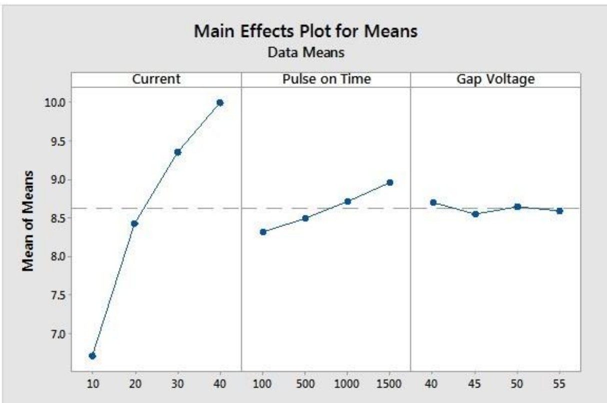


Fig. 9. Main effect plot for Ra using Al electrode.

Table 10 shows the analysis of variance (ANOVA) for surface roughness with coated electrode. The coated electrodes could also produce same effect as that of uncoated tool electrode in EDM process. However the coating could reduce the effects of creating craters over the tool electrode. Hence it could produce lower surface roughness compared with uncoated electrode. Figure 10 shows the main effects plots on Ra with coated electrodes which has been obtained using Minitab software package. It was observed that peak current has the ability to affect the size of the discharge craters and possess higher influence on determining Ra.

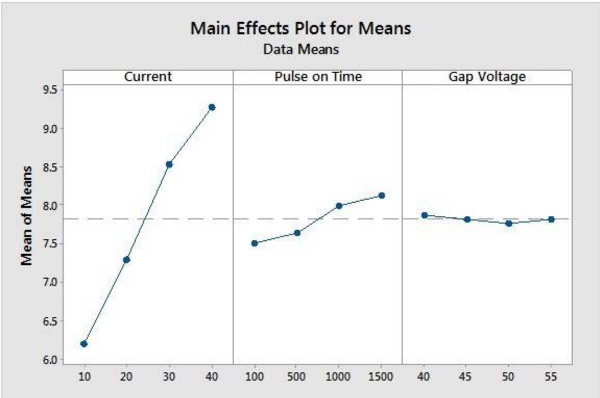


Fig. 10. Main effect plot for Ra using AlCrNi coated electrode.

While analyzing the consolidated results, if was observed that AlCrNi coated electrodes could improve the 10% lower Ra as compared with uncoated electrode owing to the less erosion made by surface coatings during the machining process as shown in Figure 11. Since the AlCrNi is hard coating which has been used to distribute the craters as uniform during machining processes, less surface roughness was observed as compared to uncoated Al electrode.

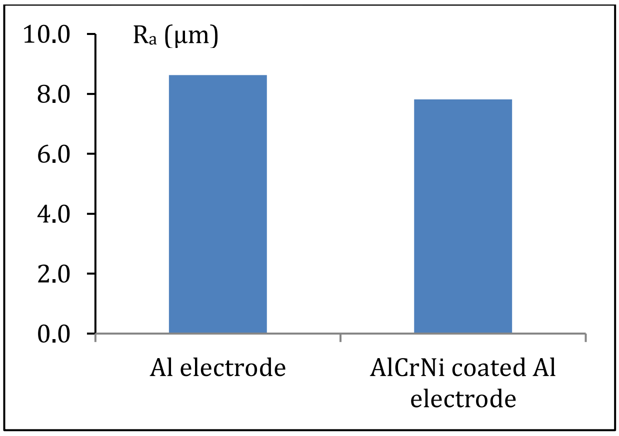
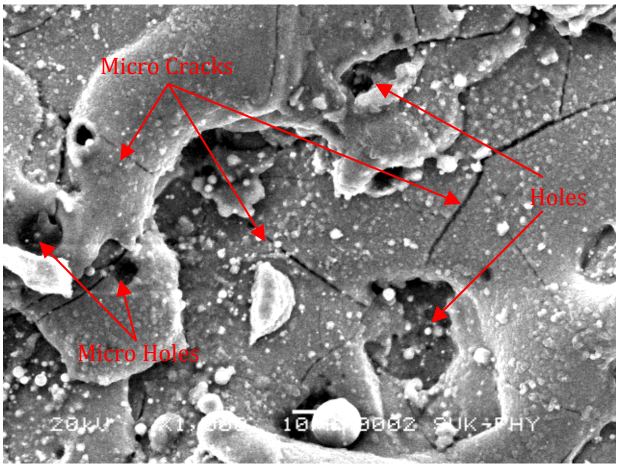
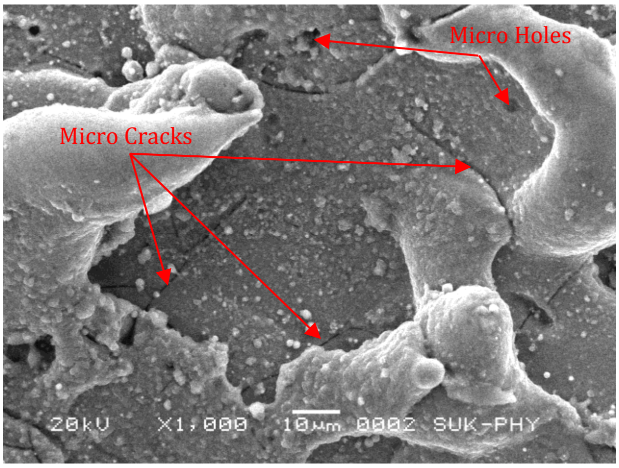


Fig. 11. Comparison of R_a values with uncoated and coated electrode.

Figure 12 shows the surface morphology analysis of machined surface using scanning electron microscopic (SEM). The JEOL JSM-6360, Mira-3 Tescan, Brno-Czech Republic, Field emission scanning electron microscope (FE-SEM) is available at Physics Department, Shivaji University, Kolhapur. SEM conducted at 1000 X and observed surface topography of both surfaces; aluminum electrode tool and AlCrNi coated electrode. It was observed that a significant amount of micro cracks over the machined surface of titanium alloy due to residual stress formation [31-32]. AlCrNi coated electrode could produce only very few micro cracks due to the thermal and electrical conductivity of the coating in EDM process. It could make very less residual stress formation over the top layer of the machined surface than uncoated tool electrode. It was concluded that AlCrNi coated tool electrode improves topography of machined surface as compared to Al electrode.



a) Machined surface with uncoated electrode



b) Machined surface with AlCrNi coated electrode

Fig. 12. SEM images of machining surfaces.

Table 4. Experimental results with uncoated Al electrode and AlCrNi coated electrode.

Expt. No.	Current	Gap Voltage	Pulse-ON Time	Uncoated Al electrode			AlCrNi coated Al electrode		
	(I)	(V_g)	(T_{ON})	MRR (gm/min)	TWR (gm/min)	R_a (μm)	MRR (gm/min)	TWR (gm/min)	R_a (μm)
1	10	40	100	0.002	0.0023	6.664	0.004	0.0001	6.111
2	10	45	500	0.0022	0.0028	6.683	0.0093	0.0002	6.162
3	10	50	1000	0.0019	0.0041	6.691	0.0086	0.0002	6.251
4	10	55	1500	0.0027	0.0029	6.815	0.0065	0.0003	6.294
5	20	45	100	0.0019	0.005	7.781	0.0053	0.0014	6.874
6	20	40	500	0.0073	0.0058	8.325	0.0107	0.0022	6.976
7	20	55	1000	0.0075	0.0076	8.662	0.0089	0.0011	7.648
8	20	50	1500	0.0111	0.0087	8.981	0.0148	0.0022	7.669
9	30	50	100	0.0053	0.0068	9.116	0.0077	0.0031	8.045
10	30	55	500	0.0097	0.0098	9.203	0.0106	0.0041	8.338
11	30	40	1000	0.0141	0.0118	9.412	0.0098	0.0037	8.768
12	30	45	1500	0.0172	0.0124	9.665	0.0099	0.0046	8.946
13	40	55	100	0.0093	0.0106	9.706	0.0133	0.0074	9.013
14	40	50	500	0.0164	0.0145	9.783	0.0125	0.0081	9.112
15	40	45	1000	0.0229	0.0177	10.112	0.0139	0.0089	9.313
16	10	40	100	0.0282	0.0212	10.391	0.0121	0.0095	9.623

Table 5. ANOVA of MRR using Al electrode.

Source	DF	SS	MS	F-Value	P-Value	Contribution %
I	3	0.000629	0.00021	45.01	0	65.93
T_{ON}	3	0.000223	0.000074	15.94	0.003	23.37
V_g	3	0.000074	0.000025	5.31	0.4	7.75
Error	6	0.000028	0.000005	-	-	2.93
Total	15	0.000954	-			
S = 0.0021585; R-Sq = 97.07%; R-Sq(adj) = 92.67%						

Table 6. ANOVA of MRR using AlCrNi coated electrode.

Source	DF	SS	MS	F-Value	P-Value	Contribution %
I	3	0.000069	0.000023	3.94	0.072	60.59
T_{ON}	3	0.000029	0.00001	1.63	0.278	31.91
V_g	3	0.000007	0.000002	0.38	0.774	5
Error	6	0.000035	0.000006	-	-	2.5
Total	15	0.00014	-			
S = 0.0024210; R-Sq = 74.83%; R-Sq(adj) = 37.07%						

Table 7. ANOVA of TWR using Al electrode.

Source	DF	SS	MS	F-Value	P-Value	Contribution %
I	3	0.000364	0.000121	53.43	0	80
T_{ON}	3	0.000062	0.000021	9.13	0.012	13.62
Vg	3	0.000015	0.000005	2.17	0.192	3.29
Error	6	0.000014	0.000002	-	-	3.11
Total	15	0.000455	-			
S = 0.0015078 ; R-Sq = 97.00%; R-Sq(adj) = 92.51%						

Table 8. ANOVA of TWR using AlCrNi coated electrode.

Source	DF	SS	MS	F-Value	P-Value	Contribution %
I	3	0.000156	0.000052	360.41	0	97.5
T_{ON}	3	0.000003	0.000001	6.27	0.028	1.87
V_g	3	0.000001	0	2.62	0.145	0.62
Error	6	0.000001	0	-	-	0.62
Total	15	0.00016	-			
S = 0.0003794; R-Sq = 99.46%; R-Sq(adj) = 98.65%						

Table 9. ANOVA of Ra using Al electrode

Source	DF	SS	MS	F-Value	P-Value	Contribution %
I	3	24.3974	8.13246	161.13	0	95
T_{ON}	3	0.9366	0.31219	6.19	0.029	3.64
V_g	3	0.0426	0.0142	0.28	0.837	0.16
Error	6	0.3028	0.05047	-	-	0.01
Total	15	25.6794	-			
S = 0.224656 ; R-Sq = 98.82%; R-Sq(adj) = 97.05%						

Table 10. ANOVA of Ra using AlCrNi coated electrode.

Source	DF	SS	MS	F-Value	P-Value	Contribution %
I	3	21.8944	7.29813	177.69	0	94.46362
T_{ON}	3	1.0166	0.33887	8.25	0.015	4.38613144
V_g	3	0.0202	0.00672	0.16	0.917	0.08715311
Error	6	0.2464	0.04107	-	-	1.0630954
Total	15	23.1776	-			
S = 0.202663; R-Sq = 98.94%; R-Sq(adj) = 97.34%						

4. CONCLUSION

In the present study, the influence of Aluminum Chromium Nickel Coated aluminium electrode was investigated on the quality criteria using EDM while machining Ti - 6Al-4V. From the experimental investigation and analysis, the following conclusions have been made.

- Aluminum Chromium Nickel coated electrode can produce 8% higher material removal rate with lower tool wear rate than uncoated electrode due to higher electrical conductivity and better surface hardness, respectively.
- The proposed coated tool electrode can produce 24% better surface finish than uncoated tool electrode due to ability of producing tiny and uniformly distributed craters over the machined surface.
- Since surface hardness is influenced by re-solidification of tool electrode, the coated tool electrode can produce higher surface hardness owing to the higher melting point of coated tool electrode.
- The Optimization of the technological parameters in EDM with coated electrode can further enhance the quality indicators. It is very much needed to concentrate in this area further.

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