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Experimental Investigation of Uncoated Electrode and PVD AlCrNi Coating on Surface Roughness in Electrical Discharge Machining of Ti-6Al-4V

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ABSTRACT

The surface texture on the EDM is an important quality indicator since it directly affects the cost of the further finishing work. The coating over the tool electrode in EDM can improve productivity, electrode wear resistance and surface quality. In the present study, the surface roughness of the EDM machined surface with coated and uncoated electrodes was evaluated. Al and AlCrNi coated Al electrode has been used for the study on machining Titanium alloy (Ti-6Al-4V). Current (I), voltage (V_g) and pulse on time (Ton) have been used as technology parameters under Taguchi method with regression model and optimal technology parameters. It was found as I and V_g are the parameters could strongly affect the surface quality. The coated tool electrode can produce better surface quality than uncoated tool electrode. The optimal technological parameters with coated and uncoated electrodes were found as I = 10 A, T_{on} = 500 µs and V_g = 40 V.

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1. INTRODUCTION

Titanium and its alloys are widely used in various fields including aerospace, nuclear, medical, etc. It is highly difficult to process such materials with traditional machining methods due to the higher strength. Electrical discharge machining (EDM) is commonly used to process this group of materials. In EDM, the machining surface quality and the machining productivity is not high [1]. Many technical solutions have been implemented to improve the machining efficiency of EDM including optimization of technological parameters, new electrode material or electrode surface layer and vibration in EDM. It has shown that the utilization of coated electrodes EDM is a great promising solution to improve machining productivity and quality. It can reduce the wear of tool electrode and production costs. However, research works on EDM using new electrode materials are mainly focused with powder metallurgical electrodes. The usage of coating electrodes are still very little. In addition, the physical and mechanical properties of the material layer of the electrode surface will directly affect the spark formation process to enhance the machining productivity and quality. Hence it is necessary to clarify the effectiveness of using coated electrodes in EDM process.

Extensive research were performed to evaluate the machinability of the electrode in EDM [2]. Many types of electrode materials (Al, Cu, Cu-W and brass) have been investigated in tool steel machining by EDM [3]. The Cu-W could produce lower surface roughness (R_a) in EDM [4]. The machining capacity with Cu-W electrode is also higher than Cu and brasselectrodes [5]. It was inferred that the formation of larger residual tensile stress in EDM process with conventional electrodes [6]. The electrode material used in EDM would affect the structure of the white layer on the machined surface layer consisting of austenite and residual stress [7, 8]. The different electrode materials are used in EDM to modify the surface quality [9 -11]. The R_a and morphology of the machining surface are strongly influenced by the changes of electrode material in EDM [12]. Recent studies have used powder metallurgical electrodes in EDM to improve

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machining efficiency with improved surface quality [13]. The TiC composite electrode can produce better surface than Cu-W electrode [14]. The powder metallurgical electrode can produce alloy layer with better surface quality and hardness[15].The composite electrodes in EDM can be fabricated with 3D printing [16]. However, it should be required that the composition of the composite mixture of the electrode material should be corrected since it would directly affect the surface quality and machinability in EDM [17].

The surface coating technology is very popular to create a different surface material from the base material, and this improves the workability of the products. Several types of electrode materials (Cu, brass, molyden and Cu-W) coated with nickel and diamond - nickel materials have been used to investigate the improvement of TWR in EDM [18]. TWR is greatly reducedin EDM with coated electrode such as diamond - nickel coated electrode. I and T_{on} are significantly affect MRR and EWR in EDM with coated electrode [19]. The regression model is determined by Taguchi - GRA, it has consistent accuracy.The higher wear resistance of the in EDM was observed with zinc coated electrode [20]. As compared to Cu electrodes, TiN or TiAlN coated Cu electrodes would be suitable for EDM better finishing [21]. The influence of parameters including V_g, I and T_{on} on the quality indicators in EDM was investigated. It was found that I was the most significant influencial parameter. The coated electrode can significantly improve MRR, TWR, R_a and machining accuracy [22]. The roughness of the machined surface with the Cu electrode has been selected to evaluate the effectiveness of coated Cu electrode including silver, nickel, zinc and epoxy. It was found that the coated electrode can significantly improve the surface quality [23]. The zinc coated electrode provides more efficient solution than many other methods [24]. The optimal values of MRR, TWR and R_a in EDM using silver coated electrode were determined by Taguchi [25]. The optimization and regression model analysis was found with accepted accuracy of practice [26]. Taguchi method is commonly used to design experiments and analyze the effect of technology parameters on quality in the EDM using powder metallurgy electrode and coated electrode [27]. Taguchi method can be very suitable for research on the effect of new coating materials on the electrode surface on the quality parameters in EDM.

The surface roughness in EDM is an indicator directly related to the choice of the further finishing method and its machining cost. Hence a research attempt is very necessary to improve surface quality in EDM. The number of studies regarding coating electrodes and the coating materials used are still very limited. In this study, the effect of technological parameters on surface roughness (R_a) in EDM using uncoated and AlCrNi coated Al electrode was investigated. The regression model development in Taguchi has identified the regression equation of the R_a. The efficiency of the coating electrode to improve the R_a and the quality of the machining surface at the optimum condition were also analyzed.

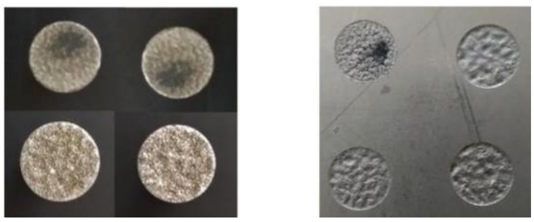
2. EXPERIMENTAL METHODOLOGY

The machining experiments were performed on CNC type Electro Discharge Machine manufactured by Electronics India Private Limitedfor machining Ti-6Al-4V alloy as shown in Figures 1 and 2. The process variables were chosen based on low, medium and high level of process parameter available at machine. All experiments were systematically planned with four level based on Taguchi method. The levels of process parameters in this study described in Table 1. Since the work deals with three factors and four levels, L16 orthogonal array (OA) was selected in the present study to evaluate quality measurement of surface roughness (R_a). Ra of machined workpiece surface was measured by contact type surface roughness tester (Taylor Hobson machine) with the cut off length of 0.8mm.

3. RESULTS AND DISCUSSION

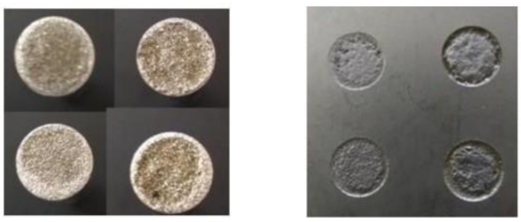
3. 1. Effects of Process Parameters on R_a using Analysis of Variance (ANOVA)

The ANOVA analysis of R_a results to find influence of parameters on quality indicators in EDM is shown inTable 2. I (F = 161.13 with Al electrode and F = 177.69 with AlCrNi coated electrode) and V_g (F = 6.19 with Al electrode and F = 8.25 with AlCrNi coated electrode) had a significant effect on R_a in EDM with Al electrode and AlCrNi coated



(a) Electrode (b) Workpiece

Figure 1. Machined surface using EDMwith Al electrode



(a) Electrode (b) Workpiece

Figure 2. Machined surface using EDM with AlCrNi electrode

TABLE 1. Experimental results from the present study

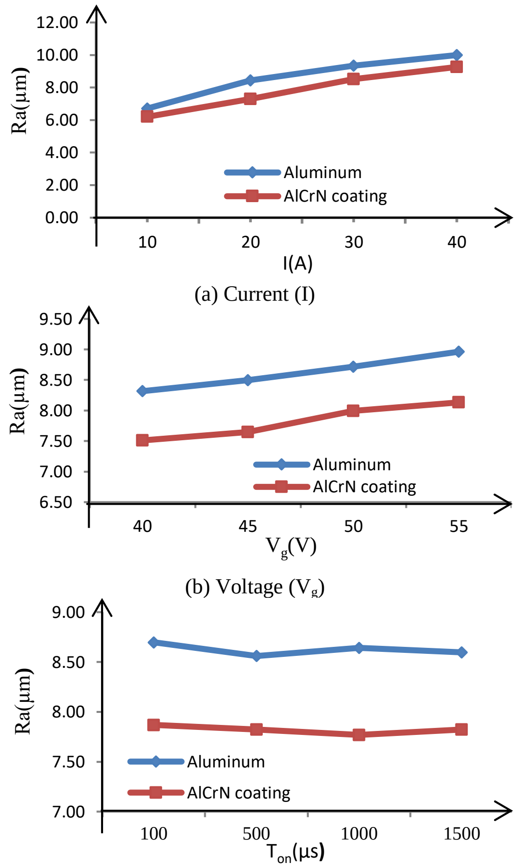
Input process parameters			R_a (µm)				Relative error (%)	
			Experimental		Calculated			
I (A)	T_{on} (µs)	V_g (V)	Al	AlCrNi coating	Al	AlCrNi coating	Al	AlCrNi coating
10	100	40	6.664	6.111	6.715	5.954	0.765	-2.576
10	500	45	6.683	6.162	6.914	6.159	3.452	-0.043
10	1000	50	6.691	6.251	7.108	6.361	6.234	1.764
10	1500	55	6.815	6.294	7.303	6.563	7.155	4.277
20	500	40	7.781	6.874	7.774	6.979	-0.085	1.533
20	100	45	8.325	6.976	8.008	7.217	-3.814	3.448
20	1500	50	8.662	7.648	8.163	7.383	-5.758	-3.463
20	1000	55	8.981	7.669	8.401	7.624	-6.461	-0.583
30	1000	40	9.116	8.045	8.829	8.001	-3.143	-0.544
30	1500	45	9.203	8.338	9.024	8.203	-1.946	-1.617
30	100	50	9.412	8.768	9.300	8.480	-1.189	-3.290
30	500	55	9.665	8.946	9.499	8.685	-1.720	-2.914
40	1500	40	9.706	9.013	9.885	9.023	1.840	0.112
40	1000	45	9.783	9.112	10.122	9.264	3.465	1.671
40	500	50	10.112	9.313	10.359	9.505	2.447	2.065
40	100	55	10.391	9.623	10.593	9.743	1.940	1.242

TABLE 2. ANOVA of R_a using Aluminum electrode and AlCrNi coated electrode

Source	DF	SS		MS		F-Value		P-Value		Contribution%	
		Al	AlCrNi	Al	AlCrNi	Al	AlCrNi	Al	AlCrNi	Al	AlCrNi
I	3	24.3974	21.8944	8.13246	7.29813	161.13	177.69	0	0	95	94.5
Vg	3	0.9366	1.0166	0.3122	0.33887	6.19	8.25	0.029	0.015	3.64	4.4
Ton	3	0.0426	0.0202	0.0142	0.00672	0.28	0.16	0.837	0.917	0.16	0.09
Error	6	0.3028	0.2464	0.05047	0.04107	-	-	-	-	0.01	1.01
Total	15	25.6794	23.1776				-				

electrode, and T_{on} (F = 0.28 with Al electrode and F = 0.16 with AlCrNi coated electrode) had a negligible effect on R_a. Based on the values of the fisher coefficient (F), I is the most significant effect (F is largest), followed by V_g and T_{on} (F is minimum), respectively. The percentage distribution of the influence of the technological parameters on R_a for both types of electrode materials is quite similar. The percentage of distribution of the influence of I is the largest (95% withAl electrode and 94.5% with AlCrNi coated electrode), it's of V_g (3.65% with Al electrode and 4.4.5% with AlCrNi coated electrode) and T_{on} is very small (0.16% with Al electrode and 0.09% with AlCrNi coated electrode).

The variation of current (I), voltage (V_g) and pulse on time (T_{on}) has affected R_a in EDM with Al electrode and AlCrNi coated electrode is shown in Figure 3. The higher I and V_g has lead to increase in R_a as shown in Figures 3a and 3b. The R_a was increased due to the increase of I and V_g which has led to the higher heating energy to produce larger size and depth of the craters on the machining surface [25]. The size and number of adhesion particles have been increased with larger melting and evaporation of the electrode material and workpiece [6]. As compared to R_a at I = 10 A, the maximum increase in R_a at I = 40A was 48.9% with the Al electrode and 49.3% with AlCrNi coated electrode. The 8.3% lower R_a has been found with AlCrNi coated electrode. The influence of I on R_a is much greater than V_g.The changes in T_{on} has resulted in negligible change in R_a with AlCrNi coated electrode as shown in Figure 3c. The R_a in EDM with Al electrode was minimum at T_{on} = 500 µs. The R_a was minimum at



(c) Pulse on time (T_{on})

Figure 3. The influence of technology parameters on R_a

T_{on} = 1000 µs with AlCrNi coated electrode. The higher T_{on} led to an increase in the spark discharge channel. However the lower peak of the spark would lead to a decrease in R_a [7].

Figure 3 also shows that R_a in EDM using AlCrNi coated electrode was smaller than with Al electrode. This shows that the machining surface quality has been improved with the coating electrode. The change of I leads to the greatest difference between the R_a of the two electrodes. The reason for the lower R_a in EDM using AlCrNi coated electrode was due to the higher thermal stability of AlCrNi coating material on the surface. This has led to higher erosive resistance of the electrode surface by the heat of the sparks. Hence the surface layer of the electrode coated with AlCrNi could be changed. The surface hardness of the electrode could also affect the roughness of the machining surface [27]. Since the coating affects the electrical conductivity of spark plasma column, it affects the discharge energy delivered per every pulse. It has considerably affected the surface roughness [27]. The difference between the thermal and electrical conductivity characteristics of the coated electrode material could affect the process of the spark formation and the energy of the generated sparks [22].

3. 2. Effects of Process Parameters on R_a using Linear Regression Model

Many methods have been used to establish regression models in EDM including Taguchi, RSM, ANN, etc. It has been inferred that EDM process requires statistical analysis and optimization to obtain optimal process parameters combinations during the machining process for better surface quality [28]. In this study, Taguchi method was used to determine the regression model of R_a in EDM using Al electrode and AlCrNi coated electrode. The analytical results on the accuracy of the regression model of R_a are shown in Tables 3 and 4. The coefficients R^2 and R^2 (adj) showed the appropriateness of the regression model. Equations (1) and (2) represent a regression model of R_a with Al electrode and AlCrNi coated electrode. The result of the R_a determined by calculation by the regression model is compared with it experimentally (Table 1 and Figure 4). It showed that the experimental and calculated maximum error of R_a was 7.15% with Al electrode as that of 4.2% with AlCrNi coated electrode. The regression model has the accuracy consistent with the experiment. The modeling has also shown that I and V_g were the main influencinal parameters on R_a in EDM using Al electrode and AlCrNi coated electrode.

$$\text{Aluminum} = 3.91504 + 0.10766 * I - 4.3465e\text{-}005 * T_{on} + 0.04319 * V_g \tag{1}$$

$$\text{AlCrNi coating} = 3.14 + 0.104 * I - 0.000039 * T_{on} + 0.0443 * V_g \tag{2}$$

3. 3. Determination of the Optimal Technology Parameters

The S/N coefficient is used to determine the optimal technology parameters. The S/N of the R_a is determined by "smaller is better" as shown in Figure 5. It has been shown that the optimum

TABLE 3. Results of the ANOVA assessment for the linear regression modelof Al electrode

Source	DF	SS	MS	F	P
Regression	3	24.1224	8.0408	61.97	0.000
Residual Error	12	1.5570	0.1297	-	-
Total	15	25.6794	-	-	-
R^2 = 93.9% R^2(adj) = 92.4%					

TABLE 4. Results of the ANOVA assessment for the linear regression model of AlCrNi coated electrode

Source	DF	SS	MS	F	P
Regression	3	22.6813	7.5604	182.79	0.000
Residual Error	12	0.4963	0.0414	-	-
Total	15	23.1776	-	-	-
R^2 = 97.9% R^2(adj) = 97.3%					

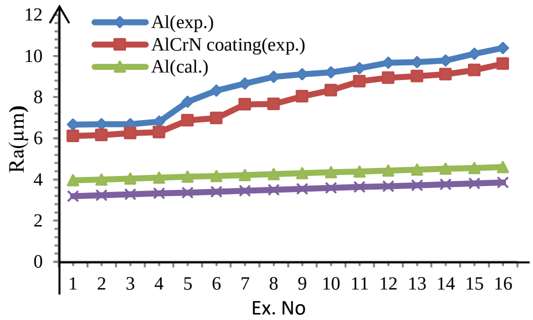
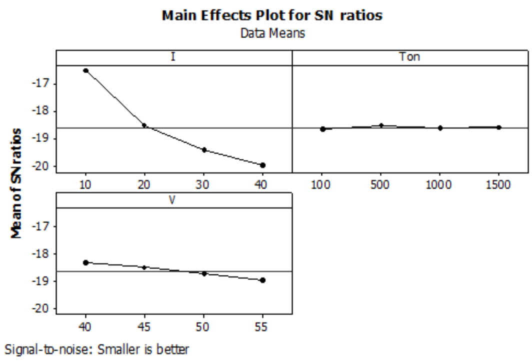
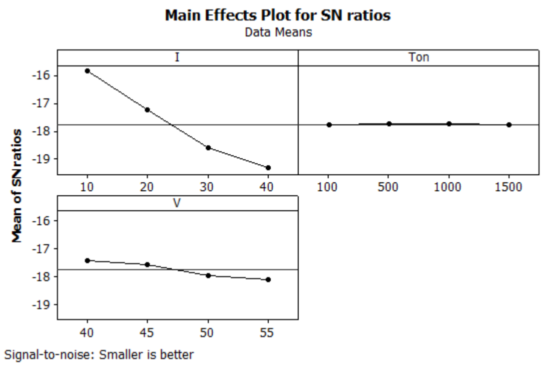


Figure 4. Compare results of experiment and calculated by regression model



(a) Al electrode



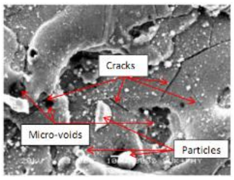
(b) AlCrNi coated electrode

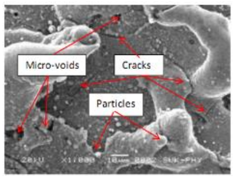
Figure 5. Main effects plot for S / N ratio of R_a

technological parameters in EDM using Al electrode and AlCrNi coated electrode are the identical as o I = 10 A, T_{on} = 500 µs and V_g = 40 V. Based on the regression model Equations (1) and (2), the optimal values for both R_a could be determined as follows $R_{a:Al}$ = 6.698 µm and $R_{a:AlCrNicoated}$ = 5.938 µm.A confirmation experiment at optimum conditions was performed and found as $R_{a:Al}$ = 6.476 µm and $R_{a:AlCrNicoated}$ = 5.858 µm. It was inferred that the error between the calculated method and experimental error was 7.2% with Al electrode and 4.3% with AlCrNi coated electrode.

3. 3. Surface Quality Analysis at Optimal Conditions

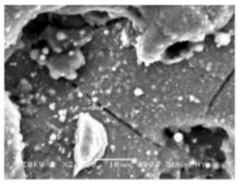
Figure 6 shows that the lower adhesion debris and micro- cracks on the machined surface in EDM has found with coated electrode as that of Al electrode. The size of particles and the micro - voids on the surface machined with coated electrode was smaller. It could also resulted in the uniform surface topography with lower surface roughness of machined surface with the AlCrNi coated electrode than Al electrode as shown in Figure 7. The size of microscopic cracks on the machined surface with Al electrode was large as shown in Figure 8. This may be due to the improved surface hardness and heat resistance properties of the coating material. It has also resulted in an increase in the erosion resistance of the AlCrNi coated electrode's surface layer with uniformly distributed surface sparks. The electrical and thermal conductivity characteristics of the coating material can facilitate the formation of sparks [24]. Hence the sparks are more uniformly distributed with the smaller beam energy. A partial arcing could be occurred with coated electrode to create tiny micro-voids.

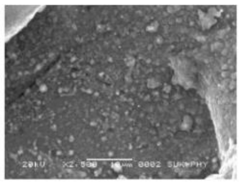




(a) Al electrode (b) AlCrNi coated electrode

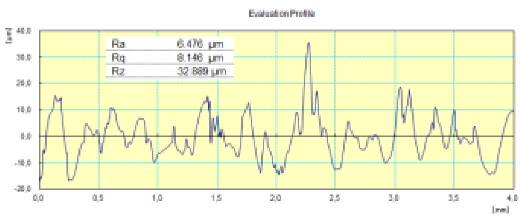
Figure 6. SEM micro-graphs of machined surface in EDM



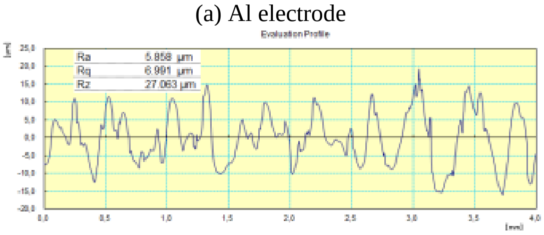


(a) Al electrode (b) AlCrNi coated electrode

Figure 7. Topography of machined surface in EDM



(a) Al electrode



(b) AlCrNi coated electrode

Figure 8. Profile of machined surface in EDM

The discharge gap size was also affected by the surface layer material of the electrode. Hence the size and number of particles adhering to the machining surface could also be improved as the discharge gap size increases. The surface quality after EDM process using AlCrNi coated electrode was observed better than Al electrode.

4. CONCLUSION

In the present study, an investigation was attempted to evaluate R_a of the EDM machined surface with coated and AlCrNi coated Al electrode. Ti-6Al-4V was utilized as specimens using regression model to get optimal technology parameters. From the detailed investigation, the following conclusions were drawn

- The AlCrNi coated tool electrode can produce better surface quality with lower surface roughness, micro cracks and voids than uncoated tool electrode due to its electrical conductivity and melting point.
- The optimal technological parameters with coated and uncoated electrodes were found as I = 10 A, T_{on} = 500 µs and V_g = 40 V with good accuracy of 4.3%.
- I and V_g are the parameters could strongly affect surface quality.
- However more clear research results are needed to comprehensively evaluate the economic and technical efficiency between coated and uncoated electrodes in EDM process.

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Persian Abstract

چکیده

بافت سطح بر روی EDM یک شاخص کیفیت مهم است زیرا مستقیماً بر هزینه کار تمام شده بعدی تأثیر می گذارد. پوشش روی الکترود ابزار در EDM می تواند باعث بهبود بهره وری ، مقاومت در برابر سایش الکترود و کیفیت سطح شود. در مطالعه حاضر ، زبری سطح ماشینکاری شده EDM با الکترودهای روکش دار و بدون روکش بررسی شد. برای مطالعه در ماشینکاری آلیاژ تیتانیوم (Ti-6Al-4V)از الکترود Al با روکش Al و AlCrNi استفاده شده است. جریان (I)، ولتاژ (Vg)و پالس به موقع (تن) به عنوان پارامترهای فناوری تحت روش تاگوچی با مدل رگرسیون و پارامترهای بهینه فناوری استفاده شده اند. از آنجا که I و Vg پارامترهایی هستند که می توانند به شدت بر کیفیت سطح تأثیر بگذارند ، مشخص شد. الکترود ابزار روکش دار می تواند کیفیت سطح بهتری نسبت به الکترود ابزار بدون روکش تولید کند. پارامترهای فن آوری بهینه با الکترودهای پوشش داده شده و بدون پوشش به عنوان I = 10 A، Ton = 500 میکرو ثانیه و Vg = 40 V پیدا شد.