

Research Article

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Influence of graphene coating in electrical discharge machining with an aluminum electrode

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Abstract: Since the cost of electrodes in electrical discharge machining (EDM) is usually too high, it leads to a significant increase in the production cost. Hence, it is important to conduct research aimed at reducing the manufacturing cost of electrodes. Currently, coated electrodes are a new process solution in EDM. It can improve the economic and technical efficiency of this technology. In this article, the efficiency of the graphene-coated aluminum (Al) electrode in the EDM for Ti–6Al–4V was analyzed and evaluated. Material removal rate and tool wear rate were used as quality indicators in this work. The research results have shown a significant improvement in quality characteristics in EDM with coated electrodes compared to EDM with uncoated electrodes. The surface quality of the specimen with coated electrodes in EDM was also improved.

Keywords: EDM, coated electrode, graphene, aluminum, MRR, TWR

1 Introduction

Titanium alloy (Ti–6Al–4V) is widely applied in many important industrial fields such as aerospace, biomedical,

nuclear, etc. Processing and manufacturing products with Ti–6Al–4V often face many difficulties, especially products with complex surfaces and small sizes [1]. At present, electrical discharge machining (EDM) is still a processing method capable of bringing high economic and technical efficiency in manufacturing titanium alloy materials. Besides the outstanding advantages of EDM compared to traditional machining methods and some other non-traditional machining methods, EDM also has some limitations such as low machining productivity and surface quality, and the electrode is worn continuously. These have led to a significant reduction in the application efficiency of EDM in practice. Therefore, this research provides process solutions to improve machining efficiency by EDM, and it is still attracting the attention of experts in this field of machining [2]. Many new process solutions were introduced such as EDM with vibration, optimization in EDM, EDM with powder mixed in dielectric, etc. EDM with coated electrodes is a process solution that is still relatively new, and it can be economically and technically viable in this area. However, different coating materials can affect the quality characteristics in EDM very differently, and research results in EDM with coated electrodes are few. Therefore, the results of studies aimed at clarifying this field still need to be further explored.

Some recent research results have shown that using copper (Cu)-coated aluminum (Al) electrodes in EDM has contributed to reducing the cost of electrode materials [3]. The production cost of the product with EDM with Cu-coated Al electrodes has been reduced by approximately 35% compared to the uncoated Cu electrodes [4]. The stiffness of the electrode fixture system of EDM with Cu-coated Al electrodes is also significantly increased because the mass of the coated electrode was only approximately two-thirds of that of the uncoated electrode [5]. The coating of the material on the electrode surface in EDM has resulted in larger machining productivity with reduced electrode wear and better surface quality. Using tin-coated electrodes in the EDM for EN24 steel has resulted in significantly reduced machining times and improved surface quality and dimensional accuracy [6]. The influence of process

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parameters on quality indicators was investigated in this study. Compared with the Cu electrode, using a silver material coated on a Cu electrode surface in EDM led to an increase in the machining productivity, and electrode wear and surface roughness were all significantly improved [7]. Using a Cu electrode coated with $\text{Al}_2\text{O}_3\text{--TiO}_2$ alloy in EDM helped to reduce the tool wear rate (TWR) by 92% and OC (overcut) by 62.5% [8]. Compared with Cu-coated materials, using Ag (silver)-coated materials on a WC (tungsten carbide) electrode surface will result in lower machining productivity [9]. EDM using a Cu–ZrB₂ coating electrode resulted in a significant reduction of the TWR [10]. The material removal rate (MRR), TWR, HV (micro-hardness), and topography of the machined surface with the multi-walled carbon nanotubes (MWCNT) Cu-coated electrode have been significantly improved [11]. In addition, the surface quality in machining with the coated electrode has also changed in a positive direction. Using a Cu-plated Gr (graphite) electrode could be a reasonable solution in EDM finishing [12]. The influence of process parameters was evaluated and analyzed, and the optimal set of process parameters was also determined [13]. The machined surface layer quality analysis showed that the Cr (chromium) and Ni (nickel) of the coating material were found in the machined surface layer. Using the zinc-coated electrode in EDM resulted in a 15.1% reduction in the machined surface roughness compared to the uncoated electrode [14]. Another study of EDM with a coated electrode showed that the surface morphology of the machined surface in EDM with a coated electrode was greatly improved [15]. The surface finishing in EDM with a coated electrode was good, and the hardness and the white layer size were also significantly improved with the white layer thickness being in the range of 11–16 μm , approximately [16]. The characteristics of the coating on the electrode surface have a remarkable influence on the topography of the machined surface in EDM [17]. The depth of cut, TWR, and OC in EDM using TiN (titanium nitride) alloy-coated WC electrodes were improved by 16.32, 26, and 18.9%, respectively [18]. Compared with TiAlN (titanium aluminum nitride) coating materials, TiN coating materials have higher efficiency [19]. In addition, the influence of voltage (U), current (I), and pulse on time (T_{on}) on the quality characteristics in EDM with coated electrodes was also determined. Zinc-coated Cu electrodes can provide higher machining efficiency than Cu electrodes in EDM for Inconel alloy IN718 [20]. The efficiency of TiN, Ag, and ZrN (zirconium nitride) coating materials in EDM has been evaluated and compared, and the results show that the TiN coating can provide a higher efficiency than the rest of the investigated materials [21]. The micro-cracks,

craters, and crumbs were uniformly distributed on the machined surface, and their dimensions were also smaller. The results of the above survey research have shown that using coated electrodes in EDM can be a good solution, but the research studies in this direction are very few. The results are mainly exploratory, and the type of coating materials and their effect on the quality characteristics in EDM have not yet been clarified.

In this article, the influence of graphene coating on the Al electrode material on the quality characteristics in EDM for Ti–6Al–4V was analyzed and clarified. The influence of U , T_{on} , and I on MRR and TWR in EDM with coated and uncoated electrodes was also presented. The surface quality of the machined surface in EDM with the coated and uncoated electrodes was also evaluated.

2 Experimental setup

The experimental work of the proposed thin-film coated and non-coated tool electrodes was conducted on a ZNC electro-discharge machine (EDM) (Electronica) available at RIT, Rajaramnagar, India. The machining process of any EDM can be controlled and evaluated with respect to various process parameters. The process parameters are factors that can provide input to machines. There are two types of process parameters available in EDM, electrical- and non-electrical-based process parameters. The flow of dielectric materials, the type of electrodes, and ultrasonic influences are considered non-electrical process parameters; however, the analysis of response variables is performed with respect to the selection of process parameters. The major electrical parameters are discharge voltage, peak current, pulse duration, pulse interval, and electrode gap, whereas the non-electrical EDM process parameters are dielectric fluid, fluid flow rate, and electrode rotation. Three electrical process parameters have been selected for the experimental work, voltage, current, and pulse on time while keeping the pulse off time and the speed of the electrode constant.

As per the literature review, preliminary experiments, and machine capabilities, three input process parameters with four levels were selected to perform experimentation. The Taguchi-based design of the experiment was developed in a systematic way to design experiments. The parameters used in this method can be studied with a small number of experimental trials. The Taguchi method is used to solve the problems of processes in the early stages of development or whose mechanism is not yet clear. Therefore, Taguchi's methods can be used to solve the technological parameters of EDM [22]. The Taguchi method solves the

Table 1: Properties of electrode materials

Properties	Uncoated Al tool electrode	Graphene-coated tool electrode
Thermal conductivity (W/m k)	204	5,300
Electrical conductivity (S/cm)	3.5×10^7	10×10^7
Melting point (°C)	660	3,675
Density (g/cm ³)	2.70	2.267

problem by using a special orthogonal matrix. Orthogonal arrays are constructed in such a way that, for each level of any one parameter, all levels of other parameters occur an equal number of times, hence creating a balanced design [23]. Hence, such designs can be used to study multiple parameters simultaneously. Additionally, both the effect of each parameter independently and their effect on each other can be studied. The process parameters in the orthogonal arrays of the Taguchi method may choose large numbers (3–50) with the possible values being different [23]. The selection of an orthogonal array depends upon the number of factors and the degrees of freedom of each factor. For this study, three parameters were considered in this experiment, and each has four levels. The suitable Taguchi design for this combination was L_{16} , which was required to perform 16 experimental runs with two types of tool electrodes: uncoated aluminum tool electrode and graphene-coated tool electrode. Similar experimental conditions were used with two types of tool electrodes to study the influence of the coated tool electrode on response variables. The response variables are chosen in such a way that these can provide useful information about the performance of the process under study. The response variables chosen for the study were the MRR and TWR. The tool electrodes have different material properties as mentioned in Table 1. This article covers the comparative study of the uncoated Al tool electrode and the graphene-coated tool electrode. Figure 1 shows a photograph of the uncoated Al tool

electrode and the graphene-coated Al tool electrode. The dimensions of the electrode are 10 mm × 100 mm diameter. The chemical vapor deposition was used for coating the graphene substrate up to 10 μm. Experimental works were executed as per the design of the experiment and the response of MRR and TWR, as mentioned in Table 2.

3 Results and discussion

3.1 Evaluation of graphene-coated materials using simulations on COMSOL

The applied voltage along with the gap between the electrode and workpiece determines the total energy of the spark. Higher voltage settings simply increase the gap to increase the potential difference. But apart from the gap, the intrinsic property of the tool material to distribute the electric potential over the surface may affect smooth heat conduction and heat generation during the process. Hence, tool wear can be minimized a little by improving the surface distribution of the electric potential. Graphene was chosen as the material and is supposed to work positively in this case. To provide a simulated backup to the above theory, this analysis was conducted. The distribution of the

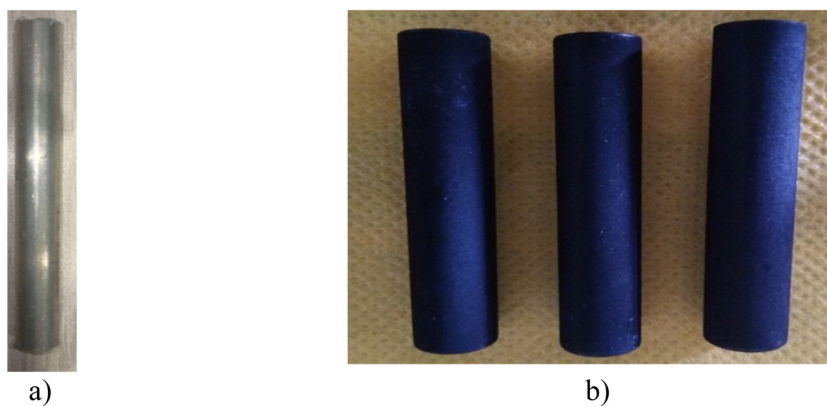
**Figure 1:** Tool electrodes used in the experimental work: (a) uncoated Al tool electrode and (b) graphene-coated Al tool electrode.

Table 2: Experimental readings

Exp. No.	Input parameters			Output parameters			
				Aluminum electrode		Graphene-coated aluminum electrode	
	Current	Voltage	Pulse on time	MRR	TWR	MRR	TWR
1	5	40	100	4.63	2.95	5.34	1.11
2	5	45	500	4.91	2.84	5.76	1.22
3	5	50	1,000	5.1	3.21	6.25	1.48
4	5	55	1,500	5.28	3.32	6.57	1.59
5	10	40	500	5.24	2.95	6.49	1.59
6	10	45	100	5.14	3.06	6.2	1.59
7	10	50	1,500	5.75	3.95	7.12	2.21
8	10	55	1,000	5.7	4.06	7.12	1.96
9	20	40	1,000	6.31	4.13	7.75	2.84
10	20	45	1,500	6.54	4.80	8.27	3.21
11	20	50	100	6.08	4.17	7.59	2.69
12	20	55	500	6.5	4.94	8.35	3.32
13	15	40	1,500	6.03	4.06	7.51	2.32
14	15	45	1,000	5.98	3.84	7.43	2.32
15	15	50	500	5.89	3.95	7.3	2.32
16	15	55	100	5.8	3.84	7.07	2.29

potential difference over the surface of the graphene-coated Al electrode and the Al electrode is shown in Figure 2. Figure 2a shows the non-coated aluminum electrode, and Figure 2b shows an aluminum electrode with a coating of graphene.

Without coating, the electric potential seems to be more crowded toward the feeder end, whereas, after coating, better distribution can be observed. This implies that the energy of the sparks will be concentrated on the tip of the electrode, and it can contribute to the facilitation of EDM.

3.2 Analysis of variance (ANOVA)

Table 3 displays the ANOVA for comparing graphene-coated Al electrodes and Al electrodes while evaluating the MRR. The Minitab software application was used to frame the ANOVA table corresponding to their mathematical models. According to the ANOVA table, the peak current has a significant impact on the MRR, which accounts for 86.22% of the contribution. As the current pulse has a huge influence on EDM, the peak current is crucial for assessing spark energy over the machining zone. With a contribution of 3.09%, the gap voltage is one of the EDM process parameters having the least impact on the MRR. The correlation coefficient R^2 value is 99.71%, which is higher than the degree of confidence. As the coated electrode may prevent erosion brought on by the spark energy, it can lower the TWR. Table 4 displays the ANOVA table for comparison of the coated and uncoated Al electrodes while assessing the TWR. The ANOVA table showed that the peak current, which accounts for 93.06% of the contribution with coated electrodes, has a considerable impact on the TWR. Pulse duration, with a contribution of 4.34%, has been the

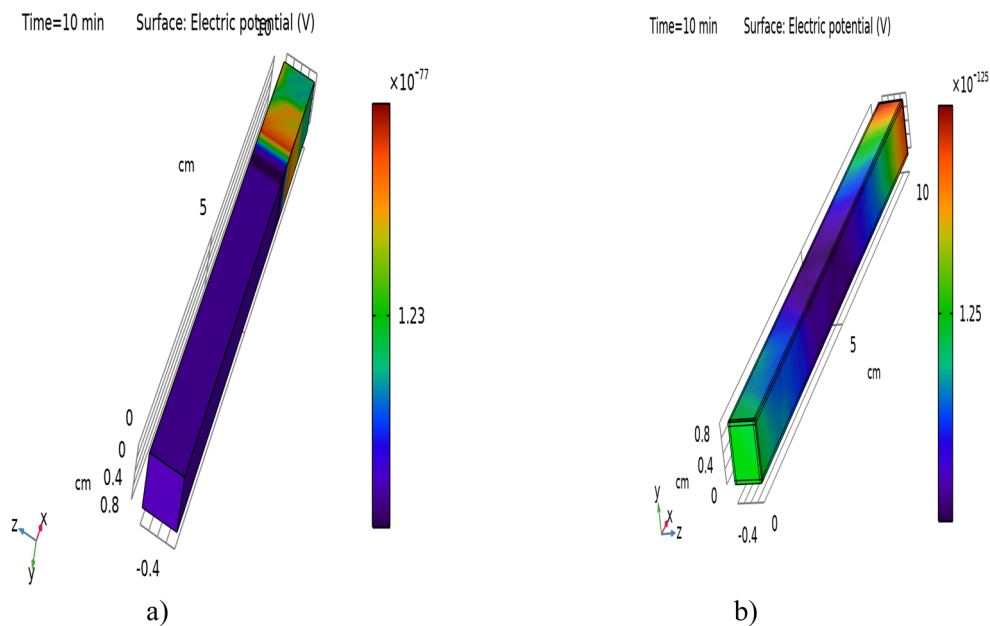
**Figure 2:** Distribution of the electric potential over the surface of the electrode: (a) Al electrode; (b) graphene-coated Al electrode.

Table 3: ANOVA results for the MRR data

Source	Sum of squares	Mean squares	F value	R ² value	R ² (pred)
EDM with an Al electrode					
Peak current	4.2342	1.4114	590.13	99.71%	97.93%
Gap voltage	0.1516	0.0505	21.12		
Pulse on time	0.5222	0.1741	72.77		
Total	4.9222	—	—		
EDM with a graphene-coated Al electrode					
Current	8.7963	2.9321	590.13	99.35%	95.36%
Gap voltage	0.5600	0.1867	21.12		
Pulse on time	1.4274	0.4758	72.77		
Total	10.8545	—	—		

second major factor affecting the TWR. From all the other EDM process variables, the gap voltage showed a minimal impact on the TWR. The R^2 correlation coefficient value is 98.18%, which is higher than the confidence interval.

3.3 Influence of parameters on the quality characteristics

3.3.1 Effect on MRR

Figure 3 shows that the MRR of the graphene-coated electrode is much higher than that of the uncoated electrode. Compared with the MRR of the Al electrode, the MRR of the coated electrode showed the largest increase of 25.68% at $I = 20$ A, and the least increase of 20.08% at $I = 5$ A (Figure 3a). Figure 3b shows that the MRR of the coated electrode is increased to the maximum and minimum by 25.04% at $U = 55$ V and 21.97% at $U = 40$ V (compared to the MRR of the uncoated electrode), respectively. By the same comparison, it was shown that the graphene coating on the Al electrode surface led to the largest increase in MRR by 24.87% with $T_{\text{on}} = 1,500$ μs , and the lowest by 21.02% at $T_{\text{on}} = 100$ μs (Figure 3c). The

reason may be that the electrical conductivity of graphene is much greater than that of aluminum. This makes the spark formation process of graphene easier, so the energy and number of sparks will be larger. This leads to the increase of melting and evaporation of the work-piece material. In addition, the density of graphene is smaller than that of aluminum, which leads to easier conductivity of the electrode. Therefore, the electrical energy of the coated electrode used for machining is also larger. The graphs in Figure 3 show that the influence of process parameters on the MRR of the coated and uncoated Al electrodes is quite similar. The increase in process parameters has led to an increase in the MRR. Compared with the uncoated Al electrode, the influence of the process parameters on the MRR with the coated electrode is larger. The slope of Figure 3a is the largest, and smallest in Figure 3b. This shows that the influence of I is the largest, and it is the smallest for U . For $I = 5$ –20 A, the MRR of the coated and uncoated electrodes increased by 33.61 and 27.66%, respectively; for $U = 40$ –55 V, the MRR of the coated and uncoated electrodes increased by 7.46 and 4.82%, respectively. Similarly for $T_{\text{on}} = 100$ –1,500 μs , the MRR of the coated and uncoated electrodes increased by 12.49 and 9.01%, respectively.

Table 4: ANOVA results for the TWR data

Source	Sum of squares	Mean squares	F value	R ² value	R ² (pred)
EDM with an Al electrode					
Current	4.4614	1.4871	17.57	91.78%	81.54%
Gap voltage	0.6141	0.2047	2.42		
Pulse on time	0.5944	0.1981	2.34		
Total	6.1777	—	—		
EDM with a graphene-coated Al electrode					
Current	6.0513	0.0271	98.84	98.18%	87.09%
Gap voltage	0.2256	0.0752	3.67		
Pulse on time	0.3475	0.1158	5.65		
Total	6.7775	—	—		

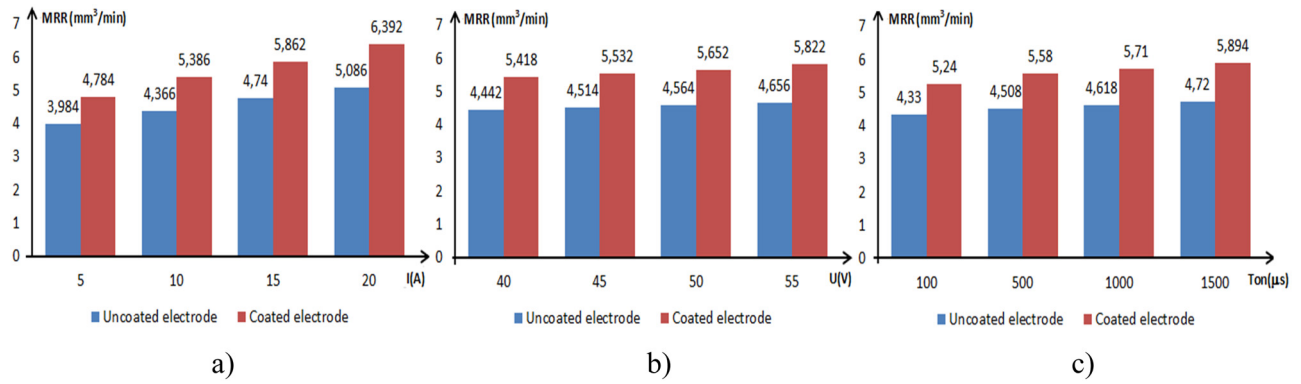


Figure 3: MRR in EDM with coated and uncoated electrodes: (a) effect of I on the MRR, (b) effect of U on the MRR, and (c) effect of T_{on} on the MRR.

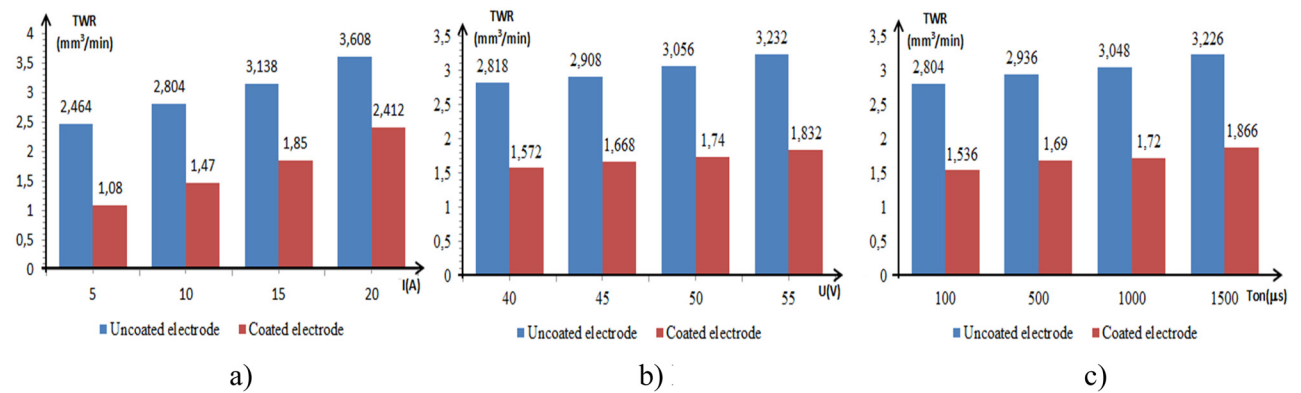


Figure 4: TWR in EDM with coated and uncoated electrodes: (a) effect of I on the TWR, (b) effect of U on the TWR, and (c) effect of T_{on} on the TWR.

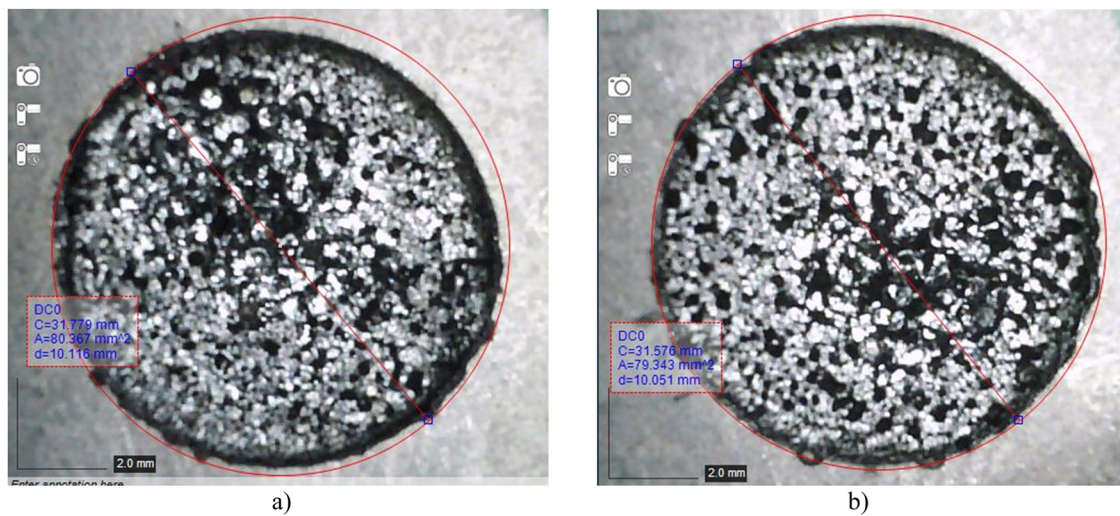


Figure 5: Machining size in EDM with coated and uncoated aluminum electrodes: (a) uncoated electrode and (b) coated electrode.

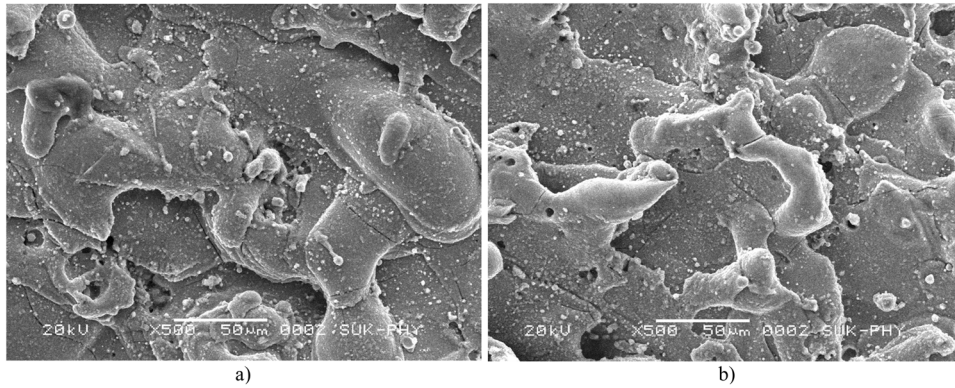


Figure 6: Machined surface topography in EDM: (a) uncoated electrode and (b) coated electrode.

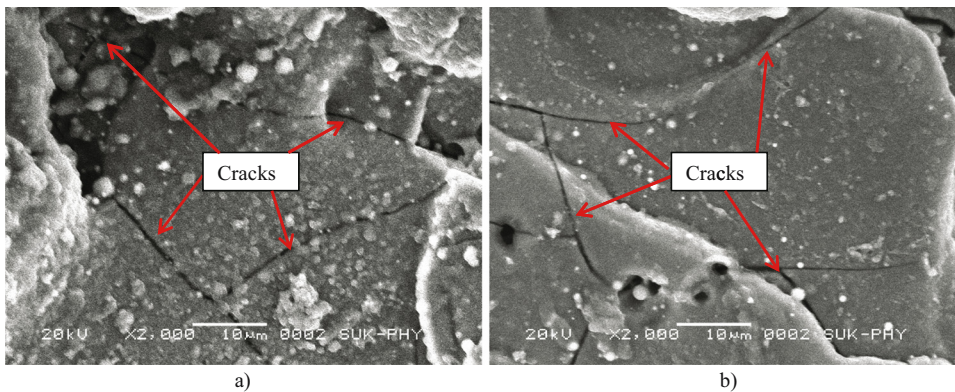


Figure 7: Cracks of the machined surface in EDM: (a) uncoated electrode and (b) coated electrode.

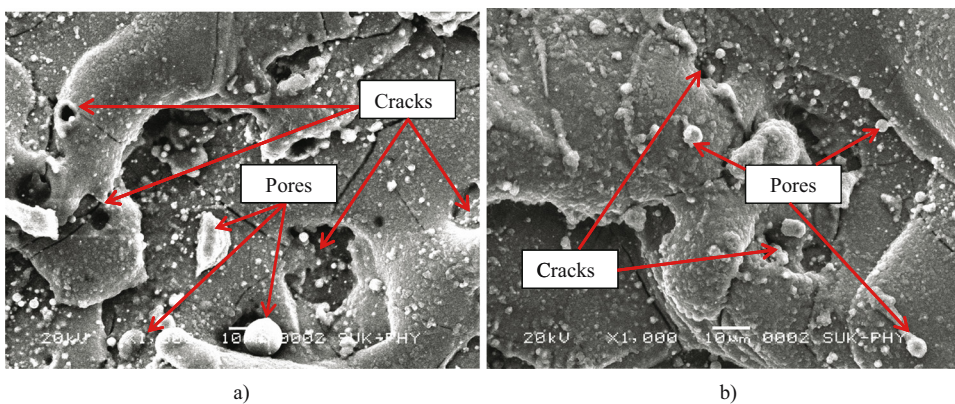


Figure 8: Adhesive particles of the machined surface in EDM: (a) uncoated electrode and (b) coated electrode.

3.3.2 Effect on TWR

The graphene coating on the Al electrode surface in the EDM for Ti-6Al-4V has contributed to significantly improving the electrode durability. Compared with the TWR of the uncoated electrode, the TWR of the coated electrode decreased as high as 56.17% at $I = 5$ A, and it

reduced to a minimum of 33.15% at $I = 20$ A (Figure 4a). Similar results are seen while comparing the TWR of the uncoated electrode with the change of U and T_{on} (Figure 4b and c). A maximum decrease in the TWR of the coated electrode is 44.22% with $U = 40$ V and 45.22% with $T_{on} = 100$ μ s; similarly, the TWR of the coated electrode decreased by 42.64% with $U = 45$ V and by 42.16% with $T_{on} = 1,500$ μ s.

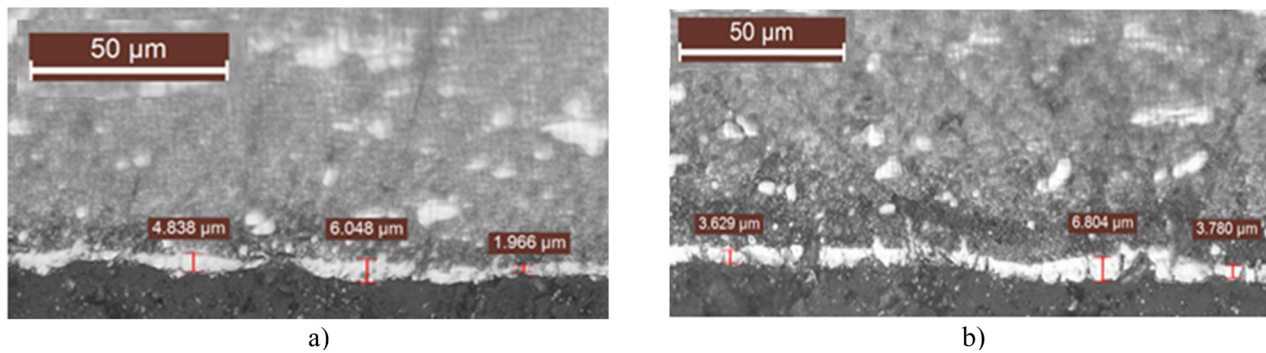


Figure 9: The white layer thickness of the machined surface in EDM: (a) uncoated electrode and (b) coated electrode.

The possible reason for this could be that the melting point of graphene is comparatively high than that of aluminum. This results in the higher erosion resistance of the coated electrode than that of the Al electrode. In addition, the electrical conductivity of graphene is higher than that of the aluminum material, and the density of the graphene material is smaller than that of the aluminum material. These factors result in easy spark formation of the coated electrode. At the same time, the thermal energy of each spark with the coated electrode is smaller, so the amount of the electrode material to be melted and evaporated is also less. The thermal conductivity of the graphene material is higher than that of Al, hence the surface temperature of the coated electrode is comparatively lower than that of the Al electrode. Therefore, it is more difficult for the surface layer of the coated electrode to melt and evaporate. The change in process parameters led to the change in the TWR of the Al electrode and the coated electrode, which is quite similar; the increase in the process parameters leads to an increase in the TWR. The increase of $I = 5\text{--}20\text{ A}$ leads to a very significant increase in the TWR, and the TWR of the coated electrode was increased by 123.33% as well as the TWR of the uncoated electrode was increased by 46.43% (Figure 4a). The increase in U and T_{on} resulted in an even strong increase in the TWR of both coated and uncoated electrodes; however, it was smaller than the increase of the TWR when I was changed. While considering the change in the voltage in the range of $U = 40\text{--}55\text{ V}$, it was shown that compared with the TWR of $U = 40\text{ V}$, the TWR of the coated electrode increased by 16.5%, and that of the uncoated electrode increased by 16.5% (Figure 4b); similarly by 14.69% at $U = 55\text{ V}$. The same result is obtained with $T_{\text{on}} = 100\text{--}1,500\text{ }\mu\text{s}$ (Figure 4c). Compared with the TWR of $T_{\text{on}} = 100\text{ }\mu\text{s}$, the TWR of the coated electrode is increased by 21.48%, and the TWR of the uncoated electrode is increased by 15.05% at $T_{\text{on}} = 1,500\text{ }\mu\text{s}$. The above results show that the influence of parameter I on the WR is stronger than those of U and T_{on} .

3.3.3 Effect of the coating material on the machined surface

Figure 5 shows that the machining hole size in EDM with the coated electrode is smaller than that with the uncoated Al electrode. The reason for this could be that the spark formation of the graphene-coated material is better than that in Al, and this results in a smaller spark energy. Therefore, the amount of overcut in the EDM with the coated electrode is smaller than that of the uncoated electrode. Therefore, the machining accuracy in EDM with the coated electrode is better than that with the uncoated electrode. The topography of the machined surface with coated and uncoated electrodes is quite similar (Figure 6). The number of craters on the machined surface with coated electrodes is more than that with Al electrodes, as the discharge of the coating material is easier. This could also be the reason that the size of micro-cracking (Figure 7), adhesion particles (Figure 8), and white layer thickness (Figure 9) of the coated electrode are smaller than those with the Al electrode [24]. The size of the adhesion particles and the thickness of any white layer distributed with the coated electrode were relatively more uniform than those with the Al electrode (Figures 8 and 9). Both the size and the number of pores on the machine surface are larger. This may be because the density and the energy of sparks formation with the coated electrode are more uniform than that in the Al electrode [25]. These results have shown that the machined surface quality with the coated electrode is better than that in the uncoated Al electrode.

4 Conclusion

In the present work, an effort was made to investigate the Ti–6Al–4V alloy using a graphene-coated Al electrode on

quality indicators in the EDM process. The following conclusions were drawn:

- The graphene-coated material produces a better concentration of the spark energy at the electrode tip area compared to that in the Al electrode.
- The graphene-coated electrode increases the MRR due to its electrical conductivity and the importance of the spark energy.
- The graphene-coated electrode reduces the TWR due to its ability to reduce erosion resistance and discharge energy.
- The graphene coating can reduce the formation of micro cracks and pores with uniform distribution of WLT.
- Coated electrodes have contributed to the improvement of several quality indicators in EDM. However, it is necessary to evaluate the economic efficiency between coated and uncoated electrodes as this will directly affect the applicability of this solution in practice.

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