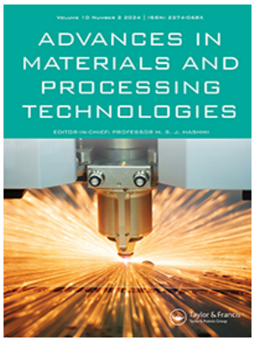

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Optimisation on machining parametres by EDM of TiN coated Ti6Al4V alloys

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ABSTRACT

This study investigated the effects of electro-erosion (EDM) processing parameters on TiN-coated Ti6Al4V alloy by the physical vapour deposition (PVD) technique. Electrode wear rate (TWR), workpiece machining rate (MRR), and surface roughness (Ra) values were determined by including discharge current, pulse time (t_{on}), and two different tool electrodes (E-Cu and CuBe) into the EDM process parameters. Variables affecting the experimental study (ANOVA) were performed depending on the analysis of variance method. For the analysed (ANOVA) TiN-coated Ti6Al4V samples, the most optimal parameters of MRR value were determined using current 12 A, t_{on} 100, and Cu electrodes. For the TWR value, the optimum parameters were examined by using current 6 A, t_{on} 100, and CuBe electrodes. Finally, 12 A current, t_{on} 100, and electrode E-Cu were analysed for the lowest Ra value. The results showed a better result in MRR and Ra with increasing discharge current, while a better result was obtained in TWR with increasing pulse duration and decreasing discharge current. In addition, it was observed that the E-Cu electrode performed better than the CuBe electrode in processing TiN-coated Ti6Al4V.

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KEYWORDS
Ti6Al4V; ANOVA; pulse on time; E-Cu and CuBe tool electrodes

1. Introduction

Ti6Al4V alloy is widely preferred in the biomedical, aerospace, and automotive industries due to its many advantages, such as acceptable biocompatibility, high-temperature stability, good corrosion resistance, excellent metallurgical, and mechanical properties [1,2]. However, it is known that Ti6Al4V alloy has the stated disadvantages, such as difficult machinability with traditional machining methods [3,4]. Regardless, due to its poor tribological (friction and wear) properties and difficult-to-machine material, its application in the intended applications is limited. The machining requirements of smaller sizes and complex geometric shapes make these materials difficult to use in conventional machining methods. Therefore, to eliminate the disadvantages of Ti6Al4V, it is necessary to use the electro-erosion machining method (EDM) with various machining performances [5].

The electro-erosion machining process (EDM) is a method of chip removal from the workpiece that involves controlled electrical melting without physical contact between

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the reverse polarised workpiece, and the tool electrode in a dielectric fluid that also serves as cooling [6]. As electrode materials for EDM, a variety of materials including copper (Cu), graphite (C), brass, tungsten (W), and steel, are frequently employed. Due to their advantageous physical characteristics, ease of machining, and low cost of raw materials, copper (Cu) and its alloys have become the most used electrode materials in recent years [7]. Copper-beryllium (CuBe) alloys are among the strongest copper alloys that were frequently employed in electrical contact applications. CuBe alloys are more expensive than E-Cu, but they are a better electrode material due to their high melting temperatures, strong wear resistance, and good machinability [8].

Peak current, pulse on time, pulse off time, and wash pressure were employed by Ohdar et al. [9] to machine soft steel using a copper electrode. They discovered that the most crucial variables were high MRR value, pulse on time, and low TWR peak current. Balasubramanian and Senthilvelan [10] processed two different materials with EDM-sintered copper, brass, and bronze electrodes. They illustrated that copper electrodes removed a high amount of material compared to sintered brass and sintered bronze electrodes, and the tool wear rate was higher for the brass electrode. Genc et al. [11] the machinability of boron alloy steel using a copper electrode was investigated by electro-erosion machining. Their research led them to the conclusion that as discharge current increased, the material removal rate (MRR), electrode wear rate (TWR), and workpiece surface roughness all increased. Jiang and Kunieda [12] reported that increasing discharge current increases material erosion volume and the processing of high-resistance materials becomes easier. Erdem et al. [13] used rotating brass electrodes with a hole in the middle to improve the surface quality of the EDM. They achieved an extremely high MRR, partly due to the dielectrics produced by adding silicon oil to a carbon powder combination. Anish et al. [14] used the Taguchi L36 design to optimise various process parameters of wire-EDM for Ti6Al4V to maximise MRR. In order to improve the Wire-EDM process of the titanium alloy for greater MRR and lower Ra. Kou and Han [15] examined the machinability of Ti alloy using EDM milling with and without rotary copper electrodes. They observed that EDM applications with a rotational electrode have a greater MRR than EDM applications without one because the electrode's rotating motion prevents the electrode's natural retraction motion from removing machining residues in the machining gap.

Although research on the impact of process factors on the EDM performance of Ti6Al4V has been conducted, no studies on the effect of TiN-coated Ti6Al4V alloy machining performance utilising copper (Cu) and copper-beryllium (CuBe) electrodes have been discovered. This research looked at MRR, TWR, and SR performance results. This article defines three objectives. The first goal is to investigate the importance and effects of EDM process parameters on performance outputs metal removal rate (MRR), electrode wear rate (TWR), and surface roughness (Ra), including both direct and indirect effects. The second goal is to identify the best settings for the EDM processing parameters while keeping all performance outputs equal in weight and importance. The final goal is to demonstrate the significance of ANOVA and complete factorial design in EDM process improvement.

Table 1. Characteristics of TiN coating material.

Coating material	Applied current	Ambient temp.	Application time	Applied voltage	Ambient pressure
TiN	50 A	450°C	40 min	400 V	4.10^{-5} torr

2. Experiment

2.1. Material and methods

In this study, the surfaces of Ti6Al4V alloy as workpiece material were cleaned with a cleaning chemical before being placed in the vacuum chamber. The parameters given in TiN were applied using the Physical Vapour Deposition (PVD) method to the Ti6Al4V alloy in Table 1.

The electrodes E-Cu and CuBe were selected. Table 2 lists the characteristics of electrode and workpiece materials. The M25A EDM Die-Sinking Machine Tool, made by Turkey's FURKAN Corp, was used for the trials (Figure 1). Throughout the experiment studies, kerosene dielectric liquid was utilised with a side washing pressure of 0.2 bar. EDM was used to treat the samples at a 0.5 mm depth.

By repeating each experiment several times, the ensuing reliability is ensured. The post-processing weight losses were computed to compute the machined workpiece volumes and worn electrodes. Volumetric losses were divided by processing time to

Table 2. Electrode and workpiece characteristics [8].

Properties	E-Cu	Cu-Be	Ti6Al4V
Ultimate tensile strength (MPa)	360	75	965
Yield strength (MPa)	320	650	895
Hardness (HBN)	120	272	342
Melting temp. (°C)	1084	955	1604
Thermal conductivity (W/mK)	386	260	7.1

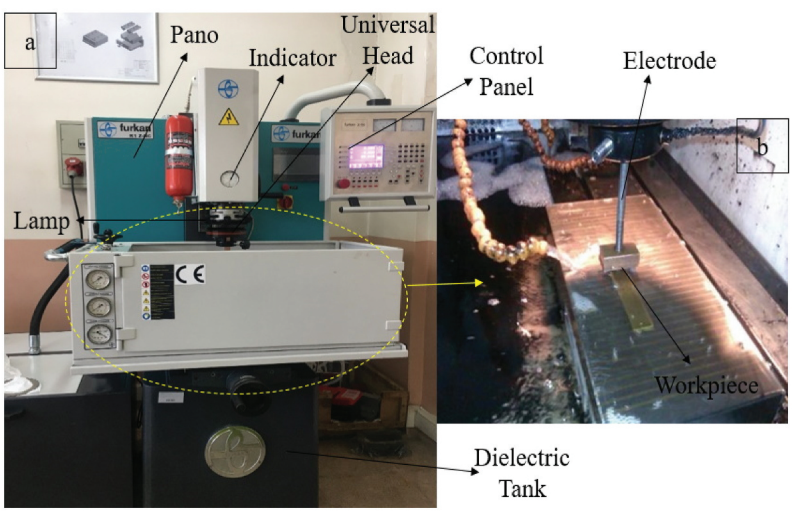

Figure 1. a) EDM setup as a whole b) Display of the EDM process.

calculate MRR (mm^3/min) and TWR (mm^3/min). Ra values were determined using a portable Mitutoyo Surftest SJ-201P equipment.

2.2. Experimental design

The experimental method's factorial design analyzes the response to various factor combinations and levels. These reactions are investigated to provide an understanding of each solid and its associated impact [16]. The factorial technique is an experiment (DOE) procedure that conducts many applications by lowering analysis time and cost to execute the method, framework better, construct, and element [17]. This original article considers greater or lesser forward sequencing to obtain ideal process parameters. The process parameter is pulse time (µs) and discharges current (A), essential factors in EDM machining. Therefore, the pull-off time is assumed to be constant at each level value. Nine samples were taken according to the 3-level and 2-factor design of the experiment for two different electrode materials using MINITAB software. Table 3 shows the variables and levels, and Table 4 shows the experimental design.

To estimate the analytical importance of the process parameters, an analysis of variance (ANOVA) was performed. ANOVA can be used to examine the criticality and cooperation of each major component at different degrees of accuracy by comparing the mean square to a measure of discovery errors [17,18]. It aids in determining the impact of individual parameters on the output parameter.

3. Result and discussion

The effect of input parameters on MRR is shown in Figure 2a. It is seen that MRR increases with increasing discharge current. Increasing the current is effective in the ionisation of the

Table 3. Control factors and levels used in the experiments.

	Levels		
Parameters	1	2	3
Pulse on time, t_{on} (µs)	25	50	100
Discharge current, I (A)	3	6	12

Table 4. Experimental design.

	Input parameters		Output parameters		
Experiment No.	Discharge current, I (A)	Pulse on time, t_{on} (µs)	MRR (mm^3/min)	TWR (mm^3/min)	R_a (µm)
1.	3	25	0.25	0.30	3.13
2.	3	50	0.41	0.50	3.93
3.	3	100	0.63	0.93	4.72
4.	6	25	1.91	0.67	3.49
5.	6	50	2.09	0.99	4.66
6.	6	100	1.91	1.19	5.85
7.	12	25	2.73	0.56	4.59
8.	12	50	2.98	0.74	5.23
9.	12	100	5.23	1.31	7.84

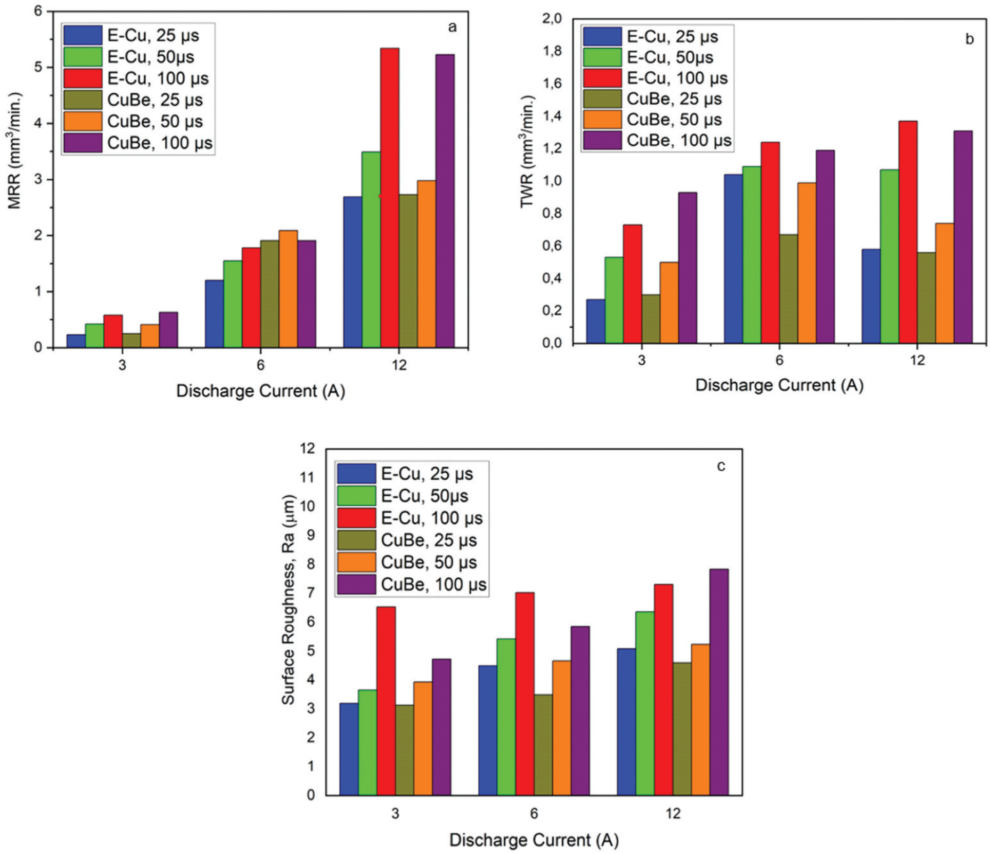

Figure 2. a) MRR, b) TWR and c) Ra under various processing conditions.

dielectric fluid and the initiation of sparking. The stronger the electric field of increasing current means the spark discharge is easier and more effective under the same gap, resulting in the removal of more significant volumes of molten material from the workpiece surface. Observing Figure 2a, the MRR increases as the discharge current increases from 3 A to 12 A and the pulse duration increases, and it can be seen that the use of Cu electrodes leads to greater MRR. In addition, when processing at low current levels, it shows that higher MRR can be obtained using CuBe electrodes compared to the Cu electrode.

Any electrode material must have good electrical conductivity and a low wear rate. Copper and copper beryllium electrodes were employed in the studies to attain these qualities. The electrical discharge energy increases by increasing the current, resulting in more stock removal from the tool electrode or increasing TWR. Figure 2b shows interaction plots for TWR variations vs. input parameters. Looking at Figure 3, it is seen that increasing the pulse duration increases TWR. High TWR appears to occur in the use of CuBe electrodes. It is seen that the electrode wear rate of using Cu electrodes will be less.

When Figure 2c is examined, it can be concluded that the surface roughness increases with an increase in discharge current and pulse duration for surface roughness (Ra). First, the increase in discharge current causes the electrode material and workpiece to melt and evaporate. The spark then allows the density to increase. For this reason, it provides the

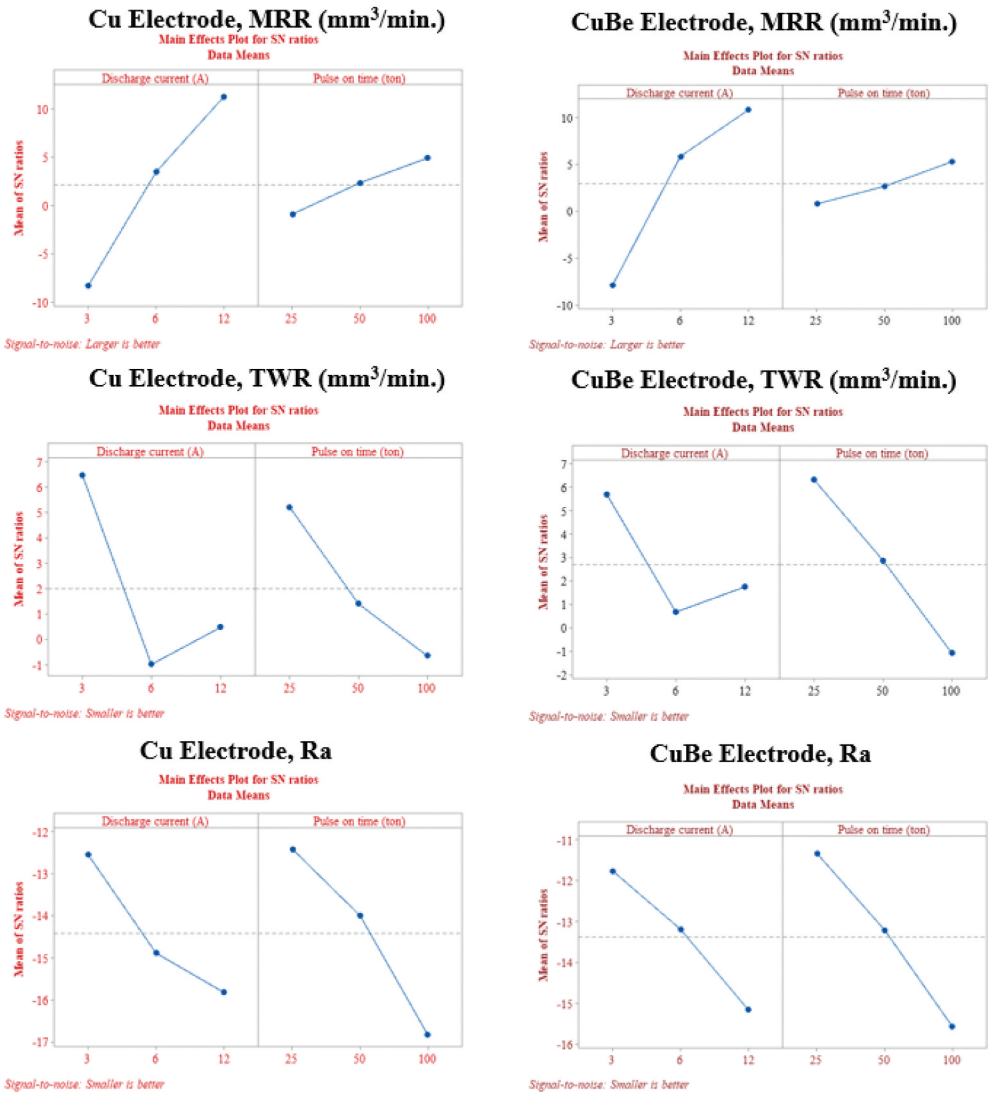

Figure 3. MRR, TWR, and Ra for the S/N graphs.

formation of crater dimensions on the surface of the workpiece material. The small size of the crater on the surface results in a decrease in surface roughness. However, it can be seen that the surface roughness (Ra) of the CuBe electrode is less compared to the Cu electrode.

3.1. Optimisation analysis

3.1.1. Analysis of variance-MRR

ANOVA determines the analysis of parameters through an analytical process applied to the results of studies. ANOVA randomly tests the outcome of each principal factor and their correlation by evaluating the mean square versus an estimated value of test errors at certain levels of precision **** [19,20]. In this review, the effect of MRR on process parameters using

Table 5. ANOVA analysis results for CuBe electrode, MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contrubiton
Discharge current, I (A)	2	15.511	7.7557	13.14	0.017	79.88361
Pulse on time, t_{on} (μs)	2	1.545	0.7725	1.31	0.365	7.956945
Error	4	2.360	0.5900	-	-	12.1543
Total	8	19.417	-	-	-	-

Table 6. ANOVA analysis results for E-Cu electrode, MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contrubiton
Discharge current, I (A)	2	18.365	9.1825	21.16	0.007	82.42079
Pulse on time, t_{on} (μs)	2	2.181	1.0906	2.51	0.196	9.78817
Error	4	1.736	0.4340	-	-	7.791042
Total	8	22.282	-	-	-	-

E-Cu and CuBe electrodes was completed using MINITAB. The most crucial parameter in machining with CuBe electrode from the determined ratio is approximately 79.88% discharge current (A), followed by 7.95% pulse time (μs). In machining with an E-Cu electrode, approximately 82.42% discharge current (A), followed by 9.78% pulse time (μs), is the essential factor. Tables 5 and 6 show results from ANOVA for MRR. This finding indicates that discharge current is the most notable processing parameter influencing MRR processing. It also shows that EDM with an E-Cu electrode will give better results for MRR.

3.1.2. Analysis of variance-TWR

ANOVA is an established statistical strategy used to examine each process parameter to give an accuracy rate. In this review, the participation level of each process parameter for TWR was calculated using MINITAB. Of the determined ratio, the most influential parameter in machining with CuBe electrode is 69.81% pulse time (μs), followed by 26.32% discharge current and 58.51% discharge current in machining with E-Cu electrode, followed by 32.91% pulse time (μs) is seen. Tables 7 and 8 show the results from ANOVA for the TWR value. When the data is examined, it is seen that using E-Cu electrodes is better for TWR.

Table 7. ANOVA analysis results for CuBe electrode, TWR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contrubiton
Discharge current, I (A)	2	0.23134	0.115668	13.64	0.016	26.32154
Pulse on time, t_{on} (μs)	2	0.61364	0.306819	36.17	0.003	69.81909
Error	4	0.03393	0.008482	-	-	3.860507
Total	8	0.87890	-	-	-	-

Table 8. ANOVA analysis results for Cu electrode, TWR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contrubiton
Discharge current, I (A)	2	0.62849	0.31425	13.67	0.016	58.51699
Pulse on time, t_{on} (μs)	2	0.35356	0.17678	7.69	0.043	32.91901
Error	4	0.09198	0.02300	-	-	8.564007
Total	8	1.07403	-	-	-	-

Table 9. ANOVA analysis results for CuBe electrode, Ra.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contrubiton
Discharge current, I (A)	2	5.878	2.9388	10.50	0.026	37.07348
Pulse on time, t_{on} (μs)	2	8.858	4.4289	15.83	0.013	55.86881
Error	4	1.119	0.2798	-	-	7.057711
Total	8	15.855	-	-	-	-

Table 10. ANOVA analysis results for E-Cu electrode, Ra.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contrubiton
Discharge current, I (A)	2	4.9923	2.4961	10.23	0.027	28.81392
Pulse on time, t_{on} (μs)	2	11.3582	5.6791	23.29	0.006	65.55581
Error	4	0.9755	0.2439	-	-	5.630267
Total	8	17.3260	-	-	-	-

3.1.3. Analysis of variance-Ra

Tables 9 and 10 show results from Ra. In the analysis of variance for surface roughness, the most crucial parameter in machining with CuBe electrode is the pulse time at 55.86%, followed by the discharge current at 37.07%. In processing with the E-Cu electrode, it was observed that there was a 65.55% pulse time and 28.81% discharge current. Considering the amount of discharge current, it is understood that the E-Cu electrode performs better for Ra. The changed parameters affected the Ra values. The application of more impulse current caused the Ra values to increase. However, poor surface quality was observed, causing the TiN coating surface to melt to evaporate [21].

3.2. Optimum parameter of EDM process

In order to provide the optimal settings MRR, TWR, and Ra within the experiment's limitations, an effort was made to estimate the ideal processing setting. Figure 3 provides the S/N graphs of the output parameters in support of this. For each output parameter, the optimum determined value of the parameters is displayed below. Table 11 also lists the ideal processing parameter combinations for specific EDM characteristics. E-Cu electrode should be preferred in determining the optimum values on Ti6Al4V alloys coated with TiN. In addition, 12 A current and 100 pulse duration are the ideal parameters for MRR and Ra, respectively. On the other hand, the CuBe electrode, 6 A current, and 100 pulse duration of optimum values were determined in TWR.

3.3. Influence of machining parameters and electrodes on MRR, TWR, Ra

According to the surface plot of the MRR, the discharge current increases, then the result of the MRR values also increases, where the effect of the pulse duration appears to be of minor importance (Figure 4). The use of E-Cu or CuBe electrode appears to have little

Table 11. Optimal settings for MRR, TWR and Ra.

Process parameters	Optimum value for MRR	Optimum value for TWR	Optimum value for Ra
Discharge current, I (A)	12	6	12
Pulse on time, t_{on} (μs)	100	100	100
Electrode	E-Cu	CuBe	E-Cu

effect on MRR. The rate of material erosion during the EDM process depends on the electrical discharge energy. According to experimental findings, the material removal rate rises as the discharge current increases. As a result, raising the peak current results in higher energy density, which raises the rate at which metal is removed. At all peak current values, the MRR increases as the pulse lengthens. The process performance is obtained by the frequency, which is determined by the spark power and the number of pulses per second. A low frequency and high power result in a high stock removal rate. Increases in material clearance accompany long-term declines in pulse frequency. A high pulse time and power combination produce greater MRR [22].

In Figure 4, changes in tool wear rate versus input EDM parameters during the machining of Ti6Al4V are illustrated via surface plots. Considering the S/N plot in Figure 3, current and pulse duration significantly affect TWR. The pulse energy during electrical discharge increases when the current is increased. As a result, metal removal

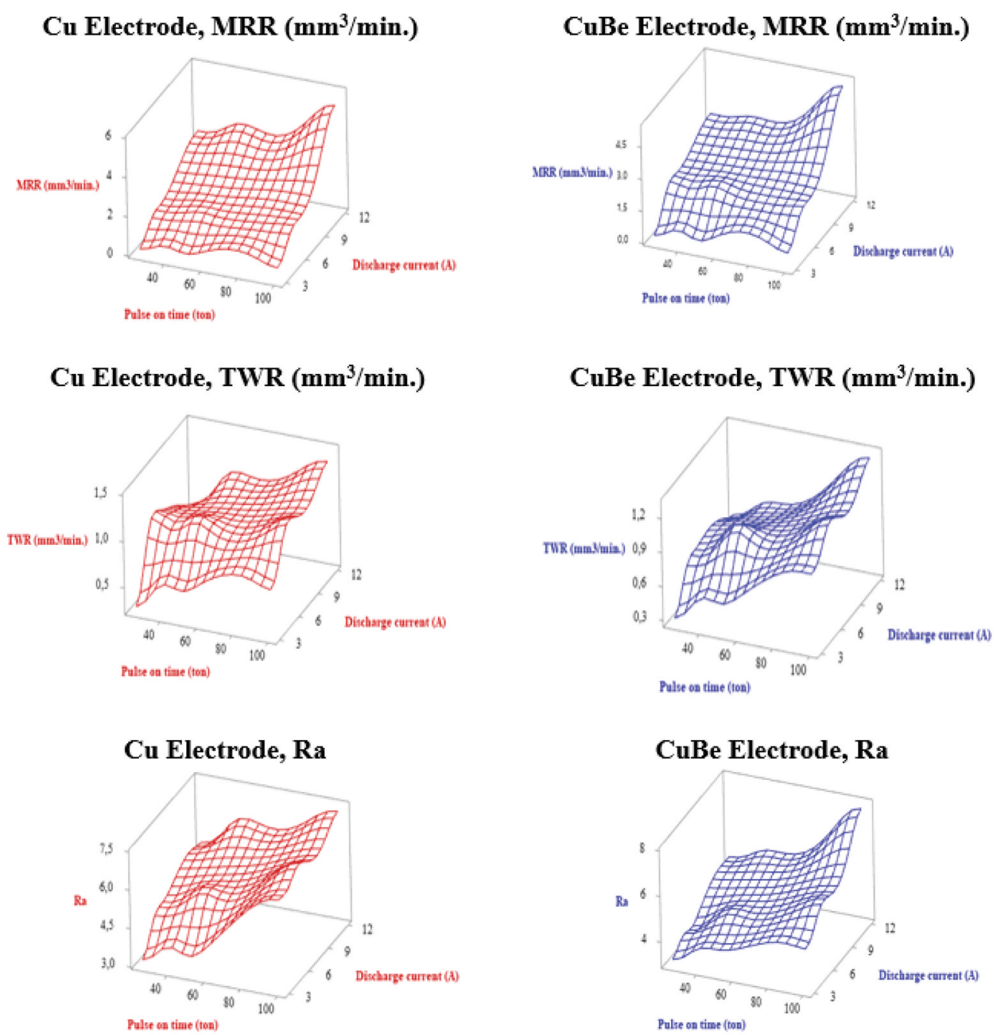

Figure 4. Surface plot for MRR, TWR, and Ra.

from copper electrodes is boosted. As a result, the TWR is higher. A rise in current suggests a significant rise in TWR. Considering Figure 4, a higher current leads to a higher tool wear rate. The increasing current generates higher spark energy and a stronger electric field, which improves the chip removal ability, thus resulting in increased tool wear. When the Ra surface graphs are examined, it is understood that the most critical parameter is the discharge current, regardless of the electrode type.

4. Conclusion

This study was carried out with a combination of three different discharge currents and pulse duration, which are the main parameters affecting the machinability of the electro-erosion method. The machining performance outputs, surface roughness Ra values, machining times, workpiece, and tool volumetric wear values were measured and calculated with MRR and TWR values. The following results were obtained from the study:

(i) The Ra value is generally lower on the treated surfaces of TiN-coated Ti6Al4V samples. The highest rate of change, with 38.7%, was found in machining using the copper tool at 100 μs and 12 A.
(ii) The increase in current and pulse duration in processing the samples increased the MRR value. The MRR value decreased in the TiN-coated Ti6Al4V sample, especially in the pure copper tools. Also, higher MRR was examined when treated with pure copper than the CuBe suit. The most significant change was an increase of 58.7% in pure copper electrode machining.
(iii) The tool wear rate increased in all machining operations with the timely increase of current and impact. In addition, copper-beryllium tool wear was higher at high current values than pure copper. Pure copper electrode wear was high in TiN-coated Ti6Al4V samples at medium and high current values. The highest rate of change occurred for the pure copper TWR value of 6 A, 25.5 μs, 37.5% higher than the copper beryllium electrode. In addition, it was observed that the E-Cu electrode performed better than the CuBe electrode in processing TiN-coated Ti6Al4V.

Disclosure statement

No potential conflict of interest was reported by the authors.

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