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ORIGINAL ARTICLE

Optimization of process parameters in micro-EDM of Ti-6Al-4V based on full factorial design

Farshid Alavi[1] **· Muhammad P. Jahan**[2]

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Abstract The objective of this study was to investigate the effects of the micro-electro-discharge machining (micro-EDM) process parameters on the machining performance parameters, in order to understand the behavior of each process parameter as well as to find out their optimal values. This research was conducted through a series of experiments using full factorial design. Analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) were employed to analyze the findings and to determine the significance of each process parameters on the response variables. The process parameters included in this study were voltage, capacitance, electrode rotational speed, and the electrode coating. Voltage and capacitance were studied separately as well as in combination in terms of the discharge energy. The response variables were consisted of machining time, tool wear, crater size, and surface micro-hardness. The findings indicated that the increase in voltage had a decreasing effect on the machining time, while it increased the crater size. The increase in capacitance resulted in decreased machining time and the tool wear, while it had an increasing effect on the surface micro-hardness. It was found that the effects of titanium nitride (TN) coating and the electrode rotational speed were not statistically significant. There was slight improvement of machining time and accuracy for increasing electrode rotational speed due to improved flushing condition, but very high electrode rotational speed was found to be unsuitable for machining accuracy. The overcut of the micro-holes was found to increase gradually with the increase of voltage and capacitance due to increase in spark gap and discharge duration, respectively. The voltage and the capacitance were found to be the two major parameters influencing the micro-EDM performance. Assuming that the importance and the weight of all response variables had been identical, the optimal process parameters for improved micro-EDM of Ti-6Al-4V were found to be TN-coated electrode, 60 V, 4700 pF, and 3000 rpm.

Keywords Micro-EDM · Ti-6Al-4V · Optimization · Machining parameters · Full factorial design

1 Introduction

Ti-6Al-4V (titanium alloy grade 5) has a wide range of applications in automotive, aerospace, and biomedical industries [1]. Nevertheless, titanium alloys are difficult to machine by conventional methods due to their poor heat conductivity, reactivity to the tool materials, cutting speed limitations, and premature failure of the cutting tools [2]. Electro-discharge machining (EDM) is a non-conventional machining process that uses the thermal energy of precisely controlled sparks for machining of any electrically conductive materials, regardless of its hardness [3]. The micro-EDM is based on the same principles applied to macro-EDM with the main differences in the radius of plasma channel, axis resolution, and the size of the electrodes [4]. Fabricating the desired micro-features using the micro-EDM process requires a profound understanding of the micro-EDM process parameters, investigating their relationship with the combination of the response variables and identifying optimal values of these parameters.

In recent years, a considerable number of studies have been conducted on both macro- and micro-scale EDM of Ti-6Al-4V.

✉ Muhammad P. Jahan
jahanmp@miamiOH.edu

1 Department of Architectural and Manufacturing Sciences, Western Kentucky University, Bowling Green, KY 42101, USA

2 Department of Mechanical and Manufacturing Engineering, Miami University, Oxford, OH 45056, USA

Fonda et al. [5] investigated the machinability of Ti-6Al-4V in the conventional EDM and reported that the increase in thermal and electrical conductivities during machining made EDM a suitable process for machining titanium alloys. There have been several studies on the effect of process parameters during the EDM of titanium alloys. Kao et al. [6] investigated the effect of machining parameters during the conventional EDM of Ti-6Al-4V and determined the optimal parameters. In their study, the optimal parameter setting was reported to be the peak current of 5 A, gap voltage of 200 V, pulse on time of 200 μs, and a duty factor of 70%. The optimal parameter setting resulted in 15% reduction in electrode wear ratio (EWR), 12% enhancement in material removal rate (MRR), and 19% improvement in surface roughness (SR) during the EDM of Ti-6Al-4V. Hasçalık and Çaydaş [7] investigated the effect of peak current and pulse duration on the MRR, tool wear ratio (TWR), and white layer thickness during EDM of Ti-6Al-4V. It was reported that the MRR, SR, TWR, and white layer thickness increased with the increase of peak current and pulse duration. In a similar study on the wire EDM of Ti-6Al-4V, Nourbakhsh et al. [8] investigated the effect of operating parameters on machining speed, tool wire breakage, and surface integrity. It was found that peak current and pulse duration were the two most important parameters influencing cutting speed and surface integrity. Ndaliman et al. [9] investigated the effect of machining parameters on the micro-hardness of Ti-6Al-4V after EDM and reported that the urea concentration and peak current were the most influential parameters influencing the surface micro-hardness. Thesiya et al. [10] studied the effect of electrode material, electrode polarity, peak current, voltage, pulse-on-time, and pulse-off-time on the recast layer and heat-affected zone during EDM of Ti-6Al-4V. They concluded that the electrode material and the polarity were the main factors influencing the formation of recast layer. Beside the studies reported above, there have been similar studies investigating the effect of process parameters on the machining performance of Ti-6Al-4V using conventional wire EDM [11–13].

In recent years, there have been multiple studies on the micro-EDM of Ti-6Al-4V. Meena and Azad [14] investigated the influence of major operating parameters (i.e., peak current, gap voltage, pulse frequency, and pulse width) on the machining performance parameters (i.e., MRR, TWR, and overcut) during the machining of micro-holes in Ti-6Al-4V using micro-EDM. Gray relational analysis (GRA) and analysis of variance (ANOVA) were used to optimize the parameters. Phipon and Pradhan [15] performed single- and multi-objective optimization of the micro-EDM process for machining micro-holes in Ti-6Al-4V. Mathematical models using response surface methodology (RSM) and genetic algorithm (GA) were used to correlate the response of the input and output parameters. They reported that the TWR can be considered as a measure of the machining efficiency and the overcut can be used as a measure of the quality of the micro-holes produced. They also reported that the solutions of multi-objective optimizations could be best described by a set of Pareto optimal non-dominated points. Kuriachen and Mathew [16] investigated the influence of various process parameters on material removal rate during micro-EDM of Ti-6Al-4V. They designed the experiments using RSM–Box-Behnken design and used ANOVA to identify the level of importance of machining parameters on the material removal rate. For micro-EDM of Ti-6Al-4V, the maximum MRR was obtained at voltage of 115 V, capacitance of 0.4 μF, electrode rotational speed of 1000 rpm, and feed rate of 18 mm/min. Sivaprakasam et al. [17] performed the modeling and experimental analysis of micro-scale wire-EDM of Ti-6Al-4V using RSM. The ANOVA was performed to investigate the influence of each parameter on the machining performance, and a GA technique was used to determine the optimal machining conditions for micro-wire-EDM of Ti-6Al-4V. The optimum machining performance obtained was MRR, kerf width, and SR of 0.01802 mm^3/min, 101.5 μm, and 0.789 μm, respectively, using the optimal machining conditions viz. voltage of 100 V, capacitance of 10 nF, and feed rate of 15 mm/s. Beside the abovementioned studies on the effect of various operating parameters during micro-EDM of Ti-6Al-4V, there have been several studies on improving the surface characteristics of Ti-6Al-4V using powder-mixed micro-EDM [18–20]. It was reported that adding conductive or semi-conductive powders in the dielectric could improve the surface integrity during micro-EDM of Ti-6Al-4V.

Although there have been several studies on the effect of process parameters on micro-EDM performance of Ti-6Al-4V, very few studies considered the effect of tool electrode coating on the machining performance. Most of the studies were designed based on one-factor-at-a-time experiments instead of studying all factors simultaneously. In addition, very

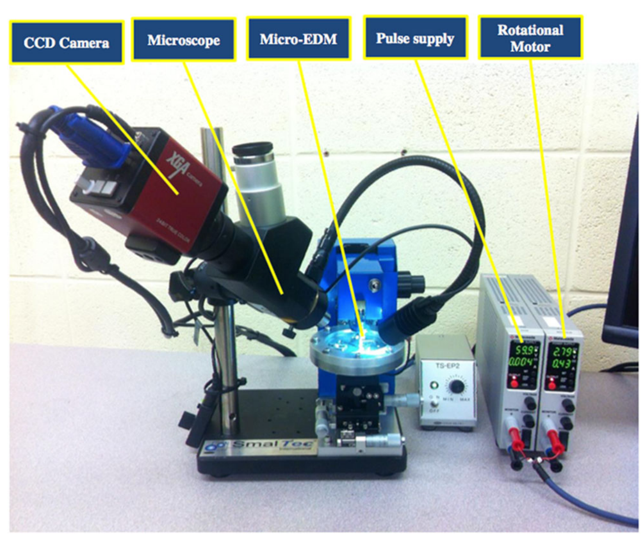


Fig. 1 Micro-EDM setup

few studies were comprehensive enough to consider surface micro-hardness and crater sizes along with the MRR, TWR, and SR. Therefore, three objectives were defined in this research. The first objective was to identify the level of importance and effects of micro-EDM process parameters on the response variables, including their main effects and interaction effects. The second objective was to find out the optimal values of the micro-EDM process parameters, provided that all response variables have an identical weight and importance. The third objective was demonstrating the role and the importance of the application of full factorial design as well as ANOVA and multivariate analysis of variance (MANOVA) in micro-EDM process improvement.

2 Experimental setup and method

A die-sinking micro-EDM machine using resistor-capacitor (RC)-type pulse generator was utilized in this study. The machine was ED009 model by Small Tech. The CCD camera and microscope were used for monitoring of micro-electro-discharge machining. The dielectric used in this study was the commercial EDM oil. Figure 1 shows the micro-EDM setup. Two types of tungsten carbide (WC) electrodes were used in this study, uncoated WC and TN-coated WC (TN-WC). All electrodes had a diameter of 300 μm. All machining trials were conducted on Ti-6Al-4V workpiece (grade 5 titanium alloy). The chemical composition and important mechanical properties of Ti-6Al-4V alloy used in this experiment are listed in Table 1.

Table 1 The chemical composition and mechanical properties of Ti-6Al-4V

Chemical composition	
Ti	Balance
Al	5.5–6.67%
V	3.5–4.5%
O	0.2%
C	0.08%
N	0.05%
Mechanical properties	
Density (kg/m^3)	4430
Melting point (°C)	1650
Electrical resistivity (Ω cm)	0.000178
Thermal conductivity (W/m K)	6.7

In this research, four process parameters were varied, namely, voltage, capacitance, electrode rotational speed, and TN coating. Response variables included the machining time, the tool wear in form of the length of the electrode used for producing each blind hole (Δl), the surface micro-hardness (VH), and the crater size. Different levels of the process parameters are shown in Table 2. Full factorial design was used for designing the experiments to evaluate both main effects and interaction effects among all process parameters. Therefore, total number of settings was 54 ($3 \times 3 \times 3 \times 2 = 54$). Table 3 shows the different settings of the micro-EDM process parameters used in this study.

Table 2 Independent variables and their levels

Process parameters	Unit	Levels		
		L1	L2	L3
Servo voltage	V	60	90	112
Capacitance	pF	30	1000	4700
Electrode rotational speed	rpm	1000	3000	4500
TN coating	–	Uncoated WC	TN-WC	

3 Results and discussions

3.1 Machining time

3.1.1 One-factor-at-a-time analysis (sorted by the discharge energy)

The machining times for blind holes with 20-μm depth were measured for different micro-EDM parameter settings. To increase the accuracy of the measurements, each trial was repeated three times and the average machining time was considered in plotting graphs. Figure 2 depicts the scatter plot between the discharge energy and the average machining time. It was found that the machining time decreased with the increase of discharge energy. This was due to the reason that with the increase of discharge energy per pulse, the crater size became broader, and hence, more material was removed for the same unit of time. The relationship between the machining time and the discharge energy could be presented by Eq. 1. The R-squared value of the curve was found to be 0.9184, which indicated a very good fit of the trend line to the experimental data.

$$\text{Machining time (s)} = 169.99 \times \text{discharge energy } (\mu\text{J})^{-0.43} \quad (1)$$

The effects of TN coating on the machining time for each level of discharge energy were calculated, and the results are shown in Fig. 3. Based on the resulting data and Fig. 3, the average machining time and its general trend for TN-WC electrode were lower than uncoated WC electrode. The lower machining time associated with titanium nitride coated tool might be associated with the comparatively higher electrical

Table 3 Process parameter settings based on full factorial design

Trial no.	Electrode type	Servo voltage (V)	Capacitance (pF)	Electrode rotation (rpm)
1	WC	60	30	1000
2	WC	60	30	2500
3	WC	60	30	4000
4	WC	60	1000	1000
5	WC	60	1000	2500
6	WC	60	1000	4000
7	WC	60	4700	1000
8	WC	60	4700	2500
9	WC	60	4700	4000
10	WC	90	30	1000
11	WC	90	30	2500
12	WC	90	30	4000
13	WC	90	1000	1000
14	WC	90	1000	2500
15	WC	90	1000	4000
16	WC	90	4700	1000
17	WC	90	4700	2500
18	WC	90	4700	4000
19	WC	112	30	1000
20	WC	112	30	2500
21	WC	112	30	4000
22	WC	112	1000	1000
23	WC	112	1000	2500
24	WC	112	1000	4000
25	WC	112	4700	1000
26	WC	112	4700	2500
27	WC	112	4700	4000
28	WC-TN	60	30	1000
29	WC-TN	60	30	2500
30	WC-TN	60	30	4000
31	WC-TN	60	1000	1000
32	WC-TN	60	1000	2500
33	WC-TN	60	1000	4000
34	WC-TN	60	4700	1000
35	WC-TN	60	4700	2500
36	WC-TN	60	4700	4000
37	WC-TN	90	30	1000
38	WC-TN	90	30	2500
39	WC-TN	90	30	4000
40	WC-TN	90	1000	1000
41	WC-TN	90	1000	2500
42	WC-TN	90	1000	4000
43	WC-TN	90	4700	1000
44	WC-TN	90	4700	2500
45	WC-TN	90	4700	4000
46	WC-TN	112	30	1000
47	WC-TN	112	30	2500
48	WC-TN	112	30	4000
49	WC-TN	112	1000	1000
50	WC-TN	112	1000	2500
51	WC-TN	112	1000	4000
52	WC-TN	112	4700	1000
53	WC-TN	112	4700	2500
54	WC-TN	112	4700	4000

conductivity of the titanium nitride coating. The high conductivity of titanium nitride coating provided on the tungsten carbide tool electrode resulted in increased electrical conductivity of the electrode, thus transferring the current between the electrode and workpiece faster. To evaluate the significance of this difference, the single-factor ANOVA analysis was conducted, as shown in Table 4. The F value was smaller than F critical value, and the P value was higher than 0.05.

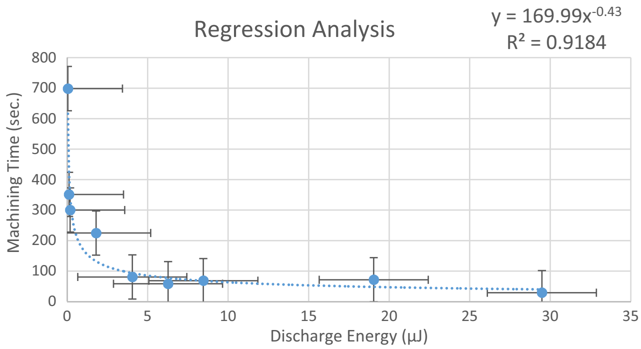


Fig. 2 The scatter plot—the discharge energy and the machining time

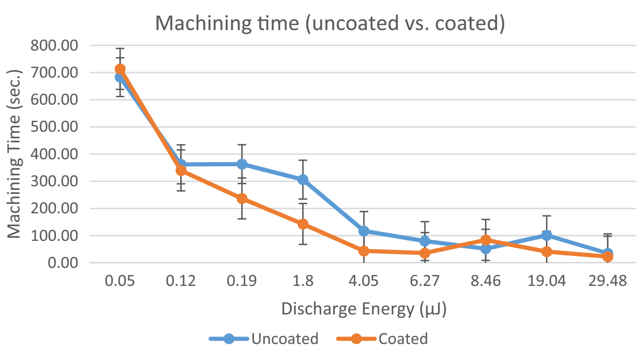


Fig. 3 The effect of TN coating on the machining times (sorted by the discharge energy from low to high values)

When sorted by the discharge energy, *F* value and *P* value indicated that the difference in the machining times with uncoated WC electrode and TN-coated WC electrode was not statistically significant.

The effects of electrode rotational speed on the machining time for each level of discharge energy were calculated, and the results are shown in Fig. 4. In the lower levels of the discharge energy, the average machining times were decreased by increasing the electrode rotational speed. With the increase of electrode rotational speed, the flushing of debris from the machining zone became more effective, thus reducing the overall machining time. To evaluate the significance of this difference, the single-factor ANOVA analysis was conducted, as shown in Table 5. It was found that the *F* value was smaller than *F* critical value and the *P* value was higher than 0.05. In addition, when sorted by the discharge energy, *F* value and *P* value indicated that the difference in the machining times for different electrode rotational speed was not statistically significant.

3.1.2 The full factorial analysis (main and interaction effects)

The main effects and the interaction effects of micro-EDM process parameters on the machining time were studied by plotting these effects and conducting analysis of variance. Figure 5 shows the main effect plot for the machining time. The plot shows the means of the machining times for each parameter level. Based on this plot, increasing the voltage, the capacitance, and the electrode rotational speed and using the TN coating resulted in reduction of the machining time. With the increase of voltage and capacitance, the discharge energy was increased, which in turn increased the machining speed. Nevertheless, the most reduction in the machining time, as shown in Fig. 5, was due to increasing the voltage and the capacitance, respectively. It should be noted that the main effects were interpreted if the interaction effects were not significant. Otherwise, the ANOVA table was used to determine whether the *P* value of the main parameters were less than α level, i.e., 0.05. Figure 6 displays the interaction effect plot for the machining time. Parallel lines in Fig. 6 indicated that most parameters had no interaction effect. The only significant interaction effect was between the voltage and the capacitance. Based on the ANOVA table shown in Table 6, the *P* value of the voltage × capacitance interaction effect was 0.000, which indicated that the interaction effect was significant. Therefore, the following step was checking the *P* value of the main parameters, which were all less than 0.05. Therefore, the main effects of the voltage, the capacitance, and their interaction were statistically significant.

The ANOVA of machining time based on the resulting data of full factorial design was conducted using Minitab 17. Table 6 shows the ANOVA table for machining time. Table 6 includes

Table 4 ANOVA for the machining time: TN-coating effect

Summary						
Groups	Count	Sum	Average	Variance		
Uncoated	9	2,102.333	233.5926	45,966.33		
Coated	9	1,663.222	184.8025	50,863.36		
ANOVA						
Source of variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	10,712.14	1	10,712.14	0.221257	0.644432	4.493998
Within groups	774,637.5	16	48,414.84			
Total	785,349.6	17				

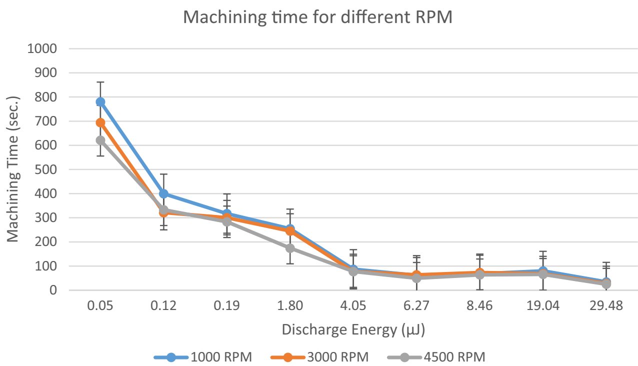


Fig. 4 The effect of electrode rotational speed on the machining times (sorted by the discharge energy from low to high values)

the sources of variation, degrees of freedom (*df*), the sum of squares (SS), contribution of the sources in the variation, the mean squares (MS), *F* values, and *P* values. In the analysis, the α level was found to be 0.05. Therefore, the *P* value that was lower than 0.05 was statistically significant. The ANOVA (Table 6) indicated that the voltage, the capacitance, and the voltage × capacitance interaction were the most important parameters in the machining time with the contributions of 65.79, 16.85, and 10.55%, respectively. These three factors were responsible for 93.19% of the variation. Moreover, the *F* values and *P* values of these factors showed that they all were statistically significant. TN coating had a contribution of 1.32%. Although the effect of coating on improving the machining time was small, it was statistically significant. Increasing the electrode rotation had the lowest effect on the machining time. From Table 6, it was inferred that the voltage was the most important parameter influencing the machining time.

3.2 Tool wear

3.2.1 One-factor-at-a-time analysis (sorted by the discharge energy)

In this study, the tool wear was calculated by measuring the difference in length of the electrode before and after machining (Δl). The tool wear for each micro-EDM parameter setting was taken as the average of three replications for that trial. Since there were six trials for each level of discharge energy, the average tool wear was calculated as the average of 18 measurements of the tool wear (Δl). Figure 7 depicts the scatter plot between the discharge energy and the average tool wear. It was found that the tool wear decreased at a specific rate of the discharge energy. This might be due to the following reasons. At low discharge energy, the machining time was higher allowing more craters to be removed from the tool electrode, thus increasing the tool wear. In addition, there were more chances of arcing and short circuiting at the lower levels of discharge energy due to comparatively shorter spark gap and ineffective flushing. This trend line used Eq. 2 to calculate the least squares fit for the tool wear. The *R*-squared value was calculated to be 0.91, which indicated a very good fit of the line to the data.

$$\text{Tool wear}\ (\mu\text{m}) = 4.3487 \times \text{discharge energy}\ (\mu\text{J})^{-0.117} \quad (2)$$

The effects of TN coating on the tool wear for each level of discharge energy were calculated, and the results are shown in Fig. 8. It was found that the tool wear was slightly higher for TN-coated tools compared to uncoated carbide tools, when machining was carried out at comparatively higher discharge energy. This might be associated with the faster removal of TN thin coating film provided on the WC tool electrode due to the higher electrical conductivity of TN-coating layer compared to core tungsten carbide. To evaluate whether there was a significant difference between the tool wear using different types of electrode, the single-factor ANOVA analysis was conducted. The results are shown in Table 7. As shown in Table 7, the *F* value was smaller than the *F* critical value and the *P* value was higher than 0.05. When sorted by the discharge energy, *F* value and *P* value indicated that the difference in the tool wear due to machining by an uncoated electrode and a TN-coated electrode was not statistically significant.

The effects of electrode rotational speed on the tool wear for each level of discharge energy were calculated, and the

Table 5 ANOVA for the machining time: electrode rotational speeds

Summary						
Groups	Count	Sum	Average	Variance		
1,000 rpm	10	2,314.074074	231.40741	52,844.79		
3,000 rpm	10	2,080.37037	208.03704	40,762.44		
4,500 rpm	10	1,881.481481	188.14815	34,009.26		
ANOVA						
Source of variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	9,377.0187	2	4,688.5094	0.110217	0.89604	3.354131
Within groups	1,148,548.4	27	42,538.83			
Total	1,157,925.4	29				

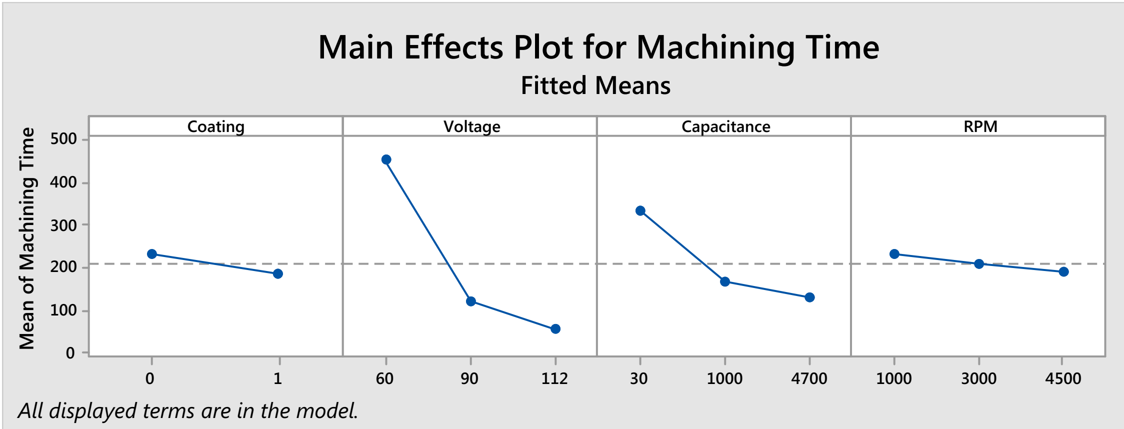


Fig. 5 The main effect plot for the machining time

results are shown in Fig. 9. In each level of the discharge energy, Fig. 9 depicts almost an identical value of the tool wear for the different electrode rotational speeds. To evaluate whether there was a significant difference between the tool wear for different electrode rotational speeds, the single-factor ANOVA analysis was conducted. The results are shown in Table 8. The *F* value was much smaller than *F* critical value, and the *P* value was higher than 0.05. When sorted by the discharge energy, *F* value and *P* value indicated that the difference in the tool wear resulting from the machining with different electrode rotational speeds was not statistically significant.

3.2.2 The full factorial analysis (main and interaction effects)

The main effects and the interaction effects of micro-EDM process parameters on the tool wear were studied by plotting these effects and conducting analysis of variance. Figure 10

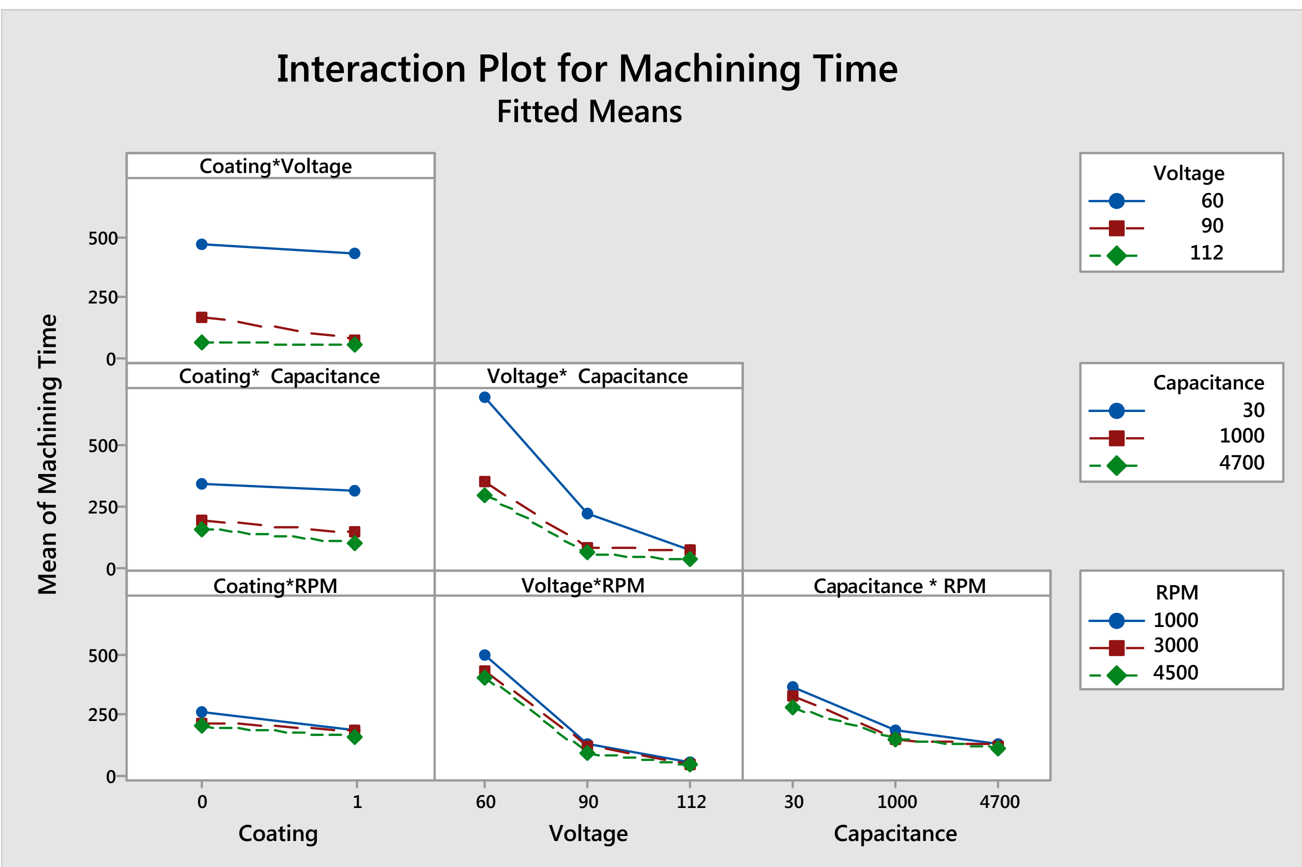


Fig. 6 The interaction effect plot for the machining time

Table 6 The ANOVA table for the machining time based on the full factorial design

Source	*df*	SS	Contribution	MS	*F* value	*P* value
Model	53	7,221,262	98.74%	136,250	159.28	0.000
Linear	7	6,191,053	84.65%	884,436	1,033.94	0.000
Coating	1	96,409	1.32%	96,409	112.71	0.000
Voltage	2	4,811,325	65.79%	2,405,662	2,812.32	0.000
Capacitance	2	1,232,683	16.85%	616,342	720.53	0.000
rpm	2	50,636	0.69%	25,318	29.60	0.000
Two-way interactions	18	887,595	12.14%	49,311	57.65	0.000
Coating × voltage	2	45,301	0.62%	22,651	26.48	0.000
Coating × capacitance	2	5,261	0.07%	2,630	3.07	0.050
Coating × rpm	2	7,276	0.10%	3,638	4.25	0.017
Voltage × capacitance	4	771,455	10.55%	192,864	225.47	0.000
Voltage × rpm	4	33,033	0.45%	8,258	9.65	0.000
Capacitance × rpm	4	25,269	0.35%	6,317	7.38	0.000
Three-way interactions	20	135,381	1.85%	6,769	7.91	0.000
Coating × voltage × capacitance	4	105,712	1.45%	26,428	30.90	0.000
Coating × voltage × rpm	4	2,996	0.04%	749	0.88	0.481
Coating × capacitance × rpm	4	9,147	0.13%	2,287	2.67	0.036
Voltage × capacitance × rpm	8	17,525	0.24%	2,191	2.56	0.013
Four-way interactions	8	7,233	0.10%	904	1.06	0.399
Coating × voltage × capacitance × rpm	8	7,233	0.10%	904	1.06	0.399

displays the main effect plot for the tool wear. This plot shows the means of the tool wear for each level of micro-EDM parameter. Based on this plot, the most significant parameter influencing the tool wear was the capacitance. The main effects of other parameters, i.e., the voltage, TN coating, and the electrode rotational speed on the tool wear, were not significant. Increasing the capacitance resulted in the reduction of the tool wear.

Figure 11 displays the interaction effect plot for the tool wear. Parallel lines indicated that there was no interaction effect. The capacitance had interaction effects with all three factors. Table 9 shows the ANOVA table of the tool wear (Δl)

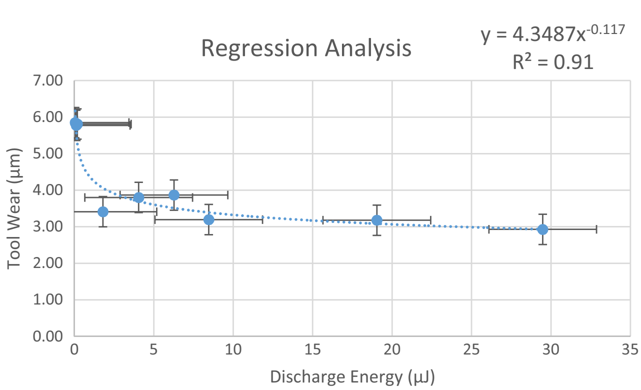


Fig. 7 The scatter plot—the discharge energy and the tool wear

based on the resulting data of the full factorial design. Based on the ANOVA (Table 9), the *P* value of the voltage × capacitance and the coating × capacitance were 0.000, which indicated that these interaction effects were significant. The interaction effect of the rpm × capacitance was not significant, because its *P* value was 0.142 that was higher than 0.05. Therefore, the *P* value of the capacitance was checked and was found to be 0.000, which was much smaller than 0.05. So, the main effect of the capacitance and its interactions with the voltage and coating were significant. Nonetheless, based on Table 9, the contribution of the voltage × capacitance and the coating × capacitance were negligible. The ANOVA (Table 9) indicated that the capacitance was the most important parameter in tool wear with the contributions of 89.72%. The *F* values and *P* values of the voltage, the coating, and the electrode rotation (rpm) showed that the effects of these parameters were not statistically significant. From the ANOVA (Table 9), it was concluded that the capacitance was the most important parameter influencing the tool wear.

3.3 Crater size

3.3.1 One-factor-at-a-time analysis (sorted by the discharge energy)

The diameters of micro-craters for all 54 trials were measured using scanning electron microscope (SEM).

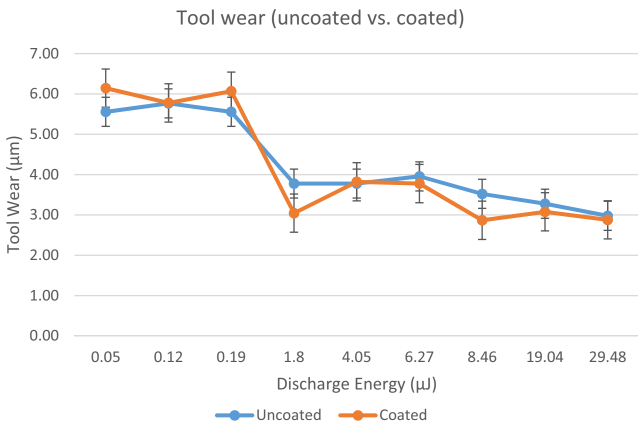


Fig. 8 The effect of TN coating on the tool wear (sorted by the discharge energy from low to high values)

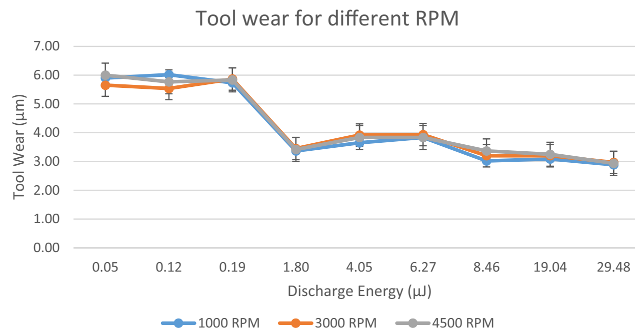


Fig. 9 The effect of electrode rotational speed on the tool wear (sorted by the discharge energy from low to high values)

Figure 12 shows the sample measurements of the crater size using a SEM image. The crater size of the machined area for each trial was the average of five crater diameters using SEM images. Since there were 6 trials for each level of discharge energy, the average crater size was the average of 30 measurements of the crater diameter. Figure 13 depicts the scatter plot between the discharge energy and the average crater size. The power trend line in the form of a curve line clearly indicated the increase of the crater size at a specific rate of the discharge energy. This was due to the fact that with the increase of discharge energy, the spark gap between the electrode and the workpiece increased. As a result of increased spark gap, the width of discharge column or sparks also increased, thus resulting in larger crater sizes. This trend line used Eq. 3 to calculate the least squares fit for the crater size. The R-squared value was 0.9931, which was a perfect fit of the line to the data.

$$\text{Crater size}\ (\mu\text{m}) = 3.4543 \times \text{discharge energy}\ (\mu\text{J})^{0.3853} \qquad (3)$$

The effects of TN coating on the crater size for each level of discharge energy were calculated, and the results are shown in Fig. 14. Based on the resulting data and Fig. 14, the crater size for machined area using a TN-WC electrode was slightly smaller than the one machined by an uncoated WC electrode. To determine whether this difference in the crater size was statistically significant, the single-factor ANOVA analysis was conducted. Table 10 shows the resulting data. The F value was smaller than F critical value, and the P value was higher than 0.05. When sorted by the discharge energy, F value and P value indicated that the difference in the crater size with uncoated electrode and TN-coated electrode was not statistically significant.

The effects of electrode rotational speed on the crater size for each level of discharge energy were calculated, and the results are shown in Fig. 15. Based on the resulting data and Fig. 15, the increasing trends of the crater size with the discharge energy were almost identical for three electrode rotational speeds. The statistical evaluation of the variance in the crater size due to changes of rpm was carried out by analysis of variance. Table 11 shows the results of the single-factor ANOVA analysis. The F value was smaller than F critical value, and the P value was much higher than 0.05. When sorted by the discharge energy, F value and P value indicated that the difference in the crater size for different electrode rotational speed was not statistically significant.

Table 7 ANOVA for the tool wear (Δl): TN-coating effect

Summary						
Groups	Count	Sum	Average	Variance		
Uncoated	9	38.16667	4.240741	1.166821		
Coated	9	37.45556	4.161728	2.022905		
ANOVA						
Source of variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	0.028093278	1	0.028093	0.017615	0.896069	4.493998
Within groups	25.51780521	16	1.594863			
Total	25.54589849	17				

Table 8 ANOVA for the tool wear: electrode rotational speeds

Summary						
Groups	Count	Sum	Average	Variance		
1000 rpm	9	37.483333	4.164815	1.755309		
3000 rpm	9	37.716667	4.190741	1.361535		
4500 rpm	9	38.233333	4.248148	1.553156		
ANOVA						
Source of Variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	0.032737	2	0.016368	0.010515	0.989545	3.402826105
Within groups	37.36	24	1.556667			
Total	37.39274	26				

3.3.2 The full factorial analysis (main and interaction effects)

The main effects and the interaction effects of micro-EDM process parameters on the crater size were studied by plotting these effects and conducting analysis of variance. Figure 16 displays the main effect plot for the crater size. This plot shows the means of the crater size for each level of micro-EDM parameter. The main effect plot showed that the voltage and the capacitance had the most influential effect on the crater size, respectively. The main effects of the electrode rotational speed and TN coating on the crater size were negligible. Increasing the voltage had the most significant effect on producing larger craters.

Figure 17 displays the interaction effect plot for the crater size. Based on the plot, almost all parameters had no interaction effects, i.e., parallel lines, except for the voltage × capacitance. Based on the ANOVA table (Table 12), the *P* value of the voltage × capacitance was 0.000, which indicated that the interaction effect was significant. The next step was to check the *P* values of the voltage and the capacitance, which were 0.000 and much smaller than 0.05. Therefore, the main effects of the voltage and the capacitance as well as their interaction effect were significant. Nonetheless, Table 12 shows that the contribution of the voltage × capacitance in crater size was only 2.68%. The ANOVA (Table 12) indicated that the voltage, the capacitance, and the voltage × capacitance interaction were the most important parameters influencing the crater size with the contributions of 89.08, 5.63, and 2.68%, respectively. It means that these factors were responsible for 97.36% of the variation in the crater size. Moreover, the *F* values and *P* values of these factors showed that they all were statistically significant. While TN coating had a negligible effect on the crater size, the electrode rotation with the *P* value of 0.302 was not statistically significant. From the ANOVA (Table 12), it was deduced that the voltage was the most important parameter influencing the crater size.

Figures 18 and 19 show the SEM images of the machined surface and corresponding parameters including discharge energy. From the qualitative comparison among the surface topography of the machined area in different level of the discharge energy, it was found that the morphology of craters produced by the electrical discharge in micro-EDM was influenced by the discharge energy. With increasing the discharge energy, the crater size and consequently the surface roughness were increased, as can be seen from Figs. 18 and 19. However, there were no significant differences in the size of craters for

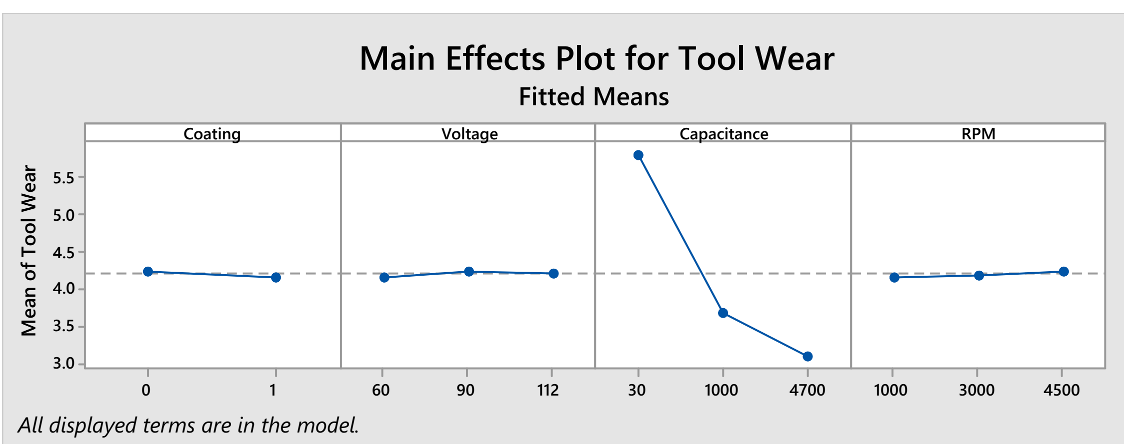


Fig. 10 The main effect plot for the tool wear

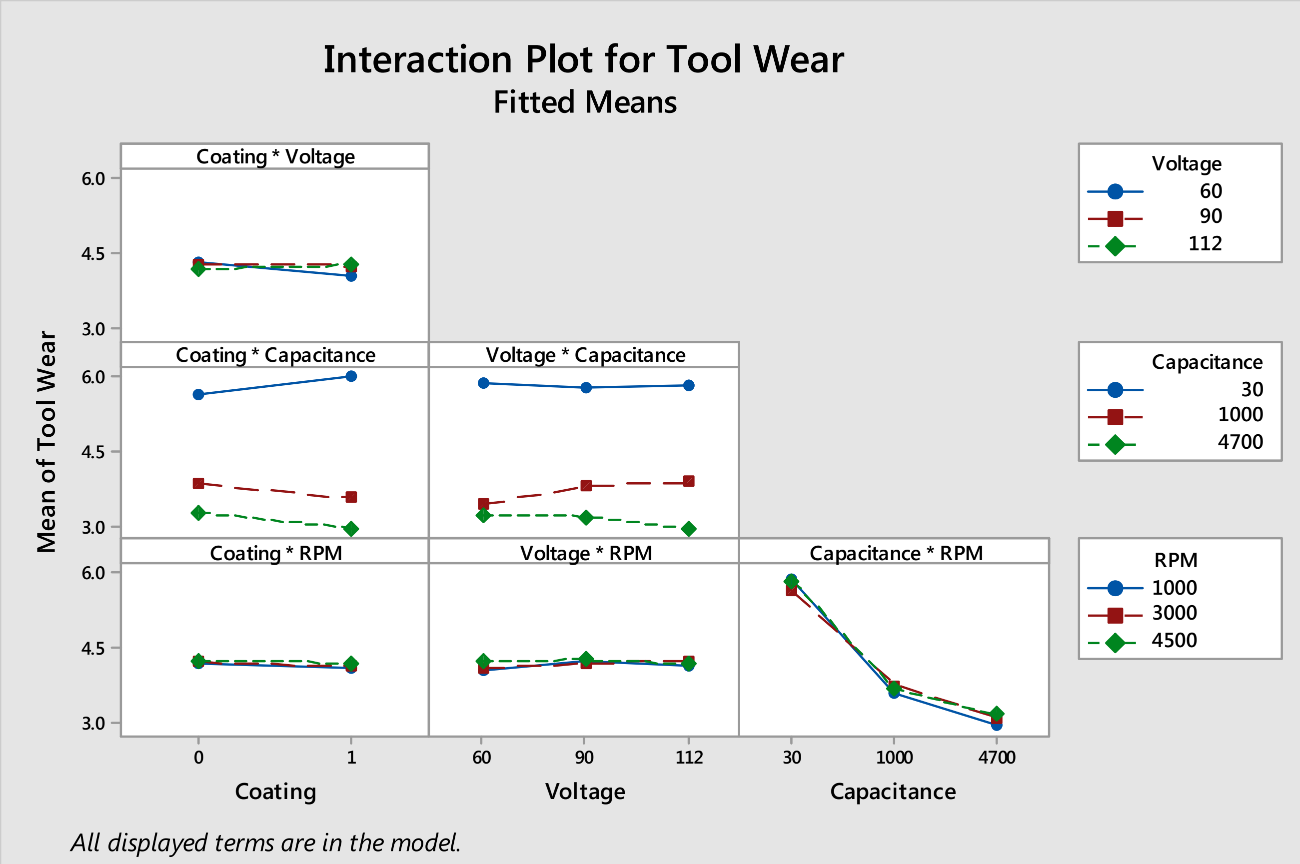


Fig. 11 The interaction effect plot for the tool wear

Table 9 The ANOVA table for the tool wear (Δl) based on the full factorial design

Source	*df*	SS	Contribution	MS	*F* value	*P* value
Model	53	233.320	95.10%	4.402	39.55	0.000
Linear	7	220.119	89.72%	31.446	282.54	0.000
Coating	1	0.253	0.10%	0.253	2.27	0.135
Voltage	2	0.260	0.11%	0.130	1.17	0.315
Capacitance	2	219.409	89.43%	109.705	985.70	0.000
rpm	2	0.196	0.08%	0.098	0.88	0.417
Two-way interactions	18	8.751	3.57%	0.486	4.37	0.000
Coating × voltage	2	0.820	0.33%	0.410	3.68	0.028
Coating × capacitance	2	4.095	1.67%	2.048	18.40	0.000
Coating × rpm	2	0.008	0.00%	0.004	0.04	0.964
Voltage × capacitance	4	2.777	1.13%	0.694	6.24	0.000
Voltage × rpm	4	0.267	0.11%	0.067	0.60	0.664
Capacitance × rpm	4	0.784	0.32%	0.196	1.76	0.142
Three-way interactions	20	3.895	1.59%	0.195	1.75	0.036
Coating × voltage × capacitance	4	2.298	0.94%	0.575	5.16	0.001
Coating × voltage × rpm	4	0.295	0.12%	0.074	0.66	0.619
Coating × capacitance × rpm	4	0.638	0.26%	0.160	1.43	0.228
Voltage × capacitance × rpm	8	0.663	0.27%	0.083	0.74	0.652
Four-way interactions	8	0.555	0.23%	0.069	0.62	0.757
Coating × voltage × capacitance × rpm	8	0.555	0.23%	0.069	0.62	0.757

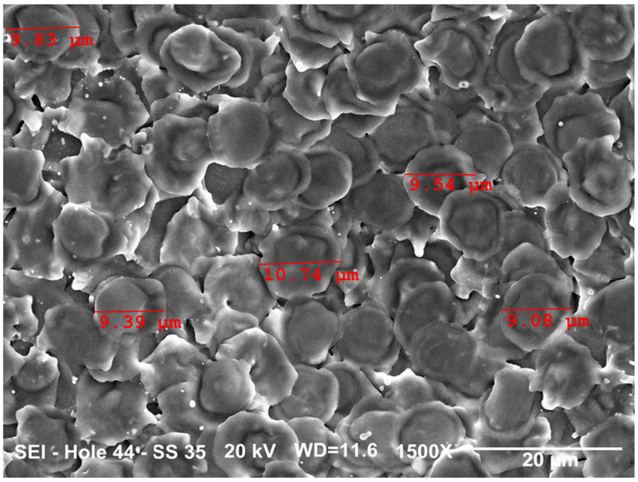


Fig. 12 The crater size measurements using a SEM image

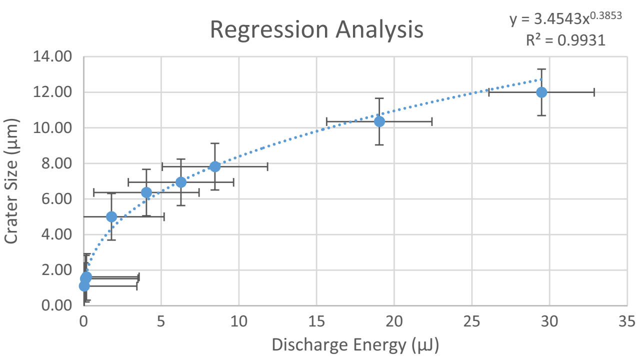


Fig. 13 The scatter plot—the discharge energy and the crater size

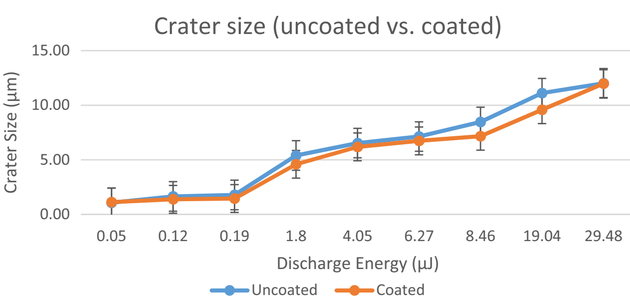


Fig. 14 The effect of TN coating on the crater size (sorted by the discharge energy from low to high values)

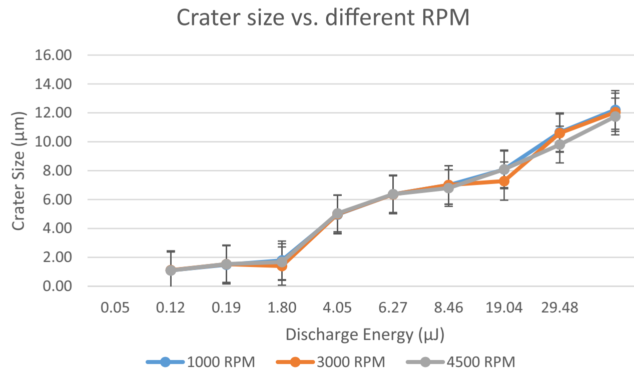


Fig. 15 The effect of electrode rotational speed on the crater size (sorted by the discharge energy from low to high values)

using uncoated and TN-coated WC tool electrodes. The findings from the SEM images about crater sizes match with the findings revealed from ANOVA analysis in Table 12.

3.4 Surface micro-hardness

3.4.1 One-factor-at-a-time analysis (sorted by the discharge energy)

The surface micro-hardness of each slot was measured on two different points. As a control group, the micro-hardness of one point from unmachined area besides each slot was also measured. The micro-hardness of each parameter setting was the average of two points for that trial. Since there were 6 trials for each level of discharge energy, the average micro-hardness was the average of 12 measurements of the micro-hardness. Figure 20 depicts the scatter plot between the discharge energy and the average micro-hardness. It was found that with the increase of discharge energy, the surface micro-hardness was increased. At higher discharge energy, comparatively higher local temperature was generated during machining due to increase in spark intensity. As a result, the machined surface suffered higher thermal variations causing an increase in micro-hardness of the surface. The power trend line in the form of a curve line indicated that surface micro-hardness

Table 10 ANOVA for the crater size: TN-coating effect

Summary						
Groups	Count	Sum	Average	Variance		
Uncoated	9	55.1987	6.1332	16.3831		
Coated	9	50.2413	5.5824	14.5726		
ANOVA						
Source of variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	1.3653	1	1.3653	0.0882	0.7703	4.4940
Within groups	247.6459	16	15.4779			
Total	249.0112	17				

Table 11 ANOVA for the crater size: electrode rotational speeds

Summary						
Groups	Count	Sum	Average	Variance		
1000 rpm	9	53.666	5.9629	16.08		
3000 rpm	9	52.325	5.8139	15.765		
4500 rpm	9	52.169	5.7966	14.481		
ANOVA						
Source of variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	0.1505	2	0.0753	0.0049	0.99514	3.403
Within groups	370.611	24	15.442			
Total	370.762	26				

increased with the discharge energy. This trend line used Eq. 4 to calculate the least squares fit for the micro-hardness. The *R*-squared value was 0.523, which was not a good fit of the line to the data. In other words, the discharge energy could only explain 52% of the increase in the micro-hardness.

$$\text{Microhardness (HV)} = 427.63 \times \text{discharge energy } (\mu\text{J})^{0.013} \quad (4)$$

The effects of TN coating on the micro-hardness for each level of discharge energy were calculated, and the results are shown in Fig. 21. It was found that there was no significant difference in the micro-hardness of the machined surfaces generated by uncoated and TN-coated WC tool electrodes. However, for using both uncoated and coated tools, the surface micro-hardness gradually increased with the increase of discharge energy. To evaluate whether there was a significant difference in the surface micro-hardness using different types of electrode, a single-factor ANOVA analysis was conducted. The results are shown in Table 13. The *F* value was smaller than *F* critical value, and the *P* value was much higher than 0.05. When sorted by the discharge energy, *F* value and *P* value indicated that the difference in the micro-hardness due to machining by an uncoated electrode and a TN-coated electrode was not statistically significant.

The effects of electrode rotational speed on the micro-hardness for all levels of the discharge energy were calculated. The results are shown in Fig. 22. It was found that the electrode rotational speed had no significant effect on surface micro-hardness. To evaluate whether there was a significant difference between the micro-hardness for different electrode rotational speeds, the single-factor ANOVA analysis was conducted (Table 14). The *F* value was smaller than the *F* critical value, and the *P* value was higher than 0.05. When sorted by the discharge energy, *F* value and *P* value indicated that the difference in the micro-hardness resulting from the machining with the different electrode rotational speeds was not statistically significant.

3.4.2 The full factorial analysis (main and interaction effects)

The main effects and the interaction effects of micro-EDM process parameters on the surface micro-hardness were

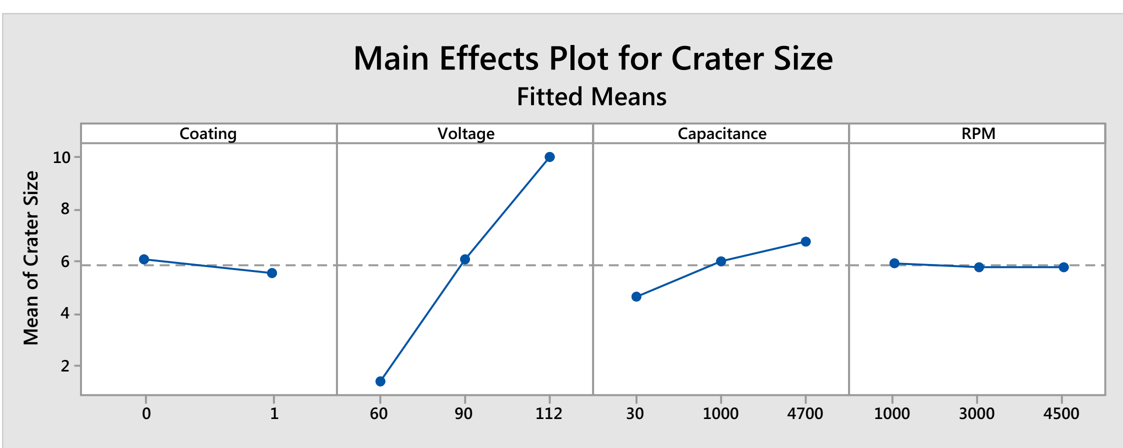


Fig. 16 The main effect plot for the crater size

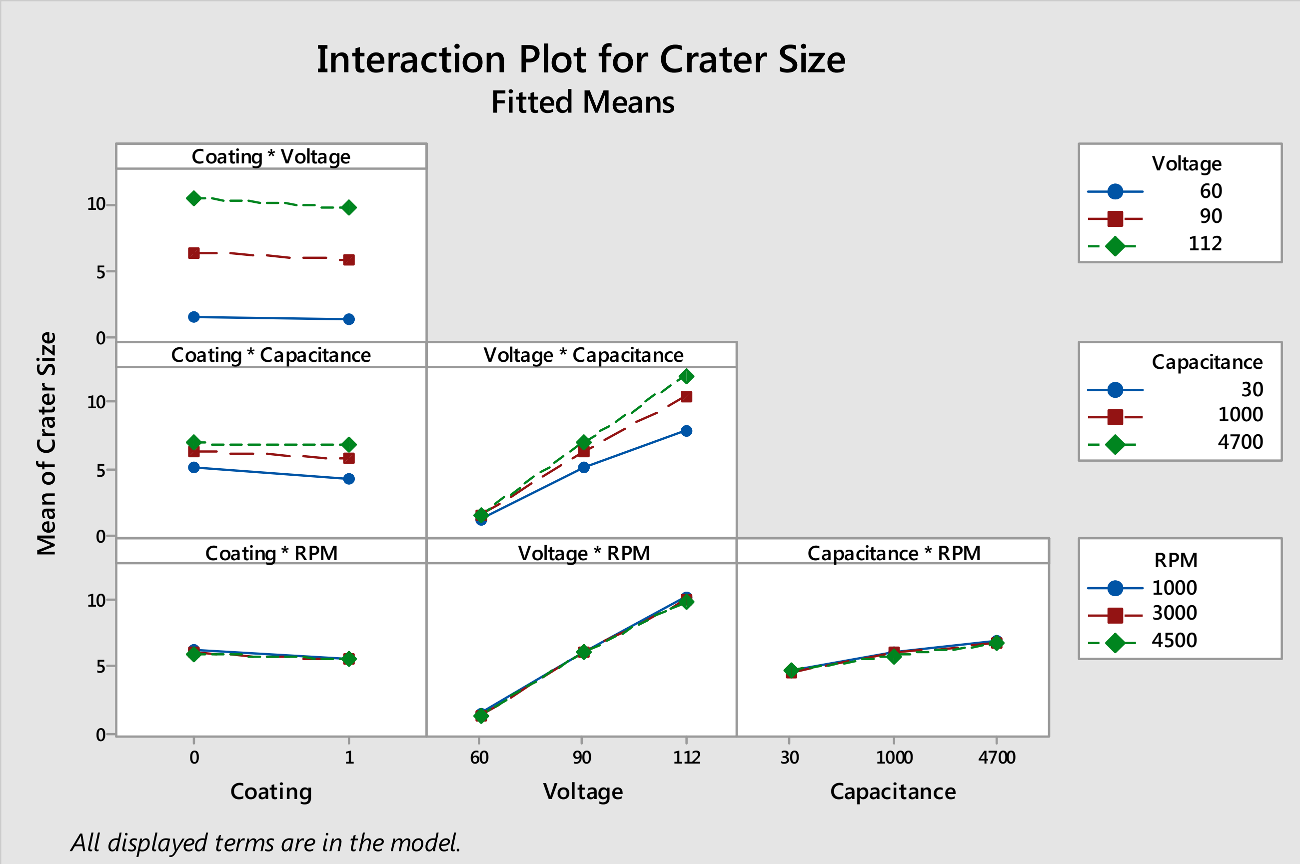


Fig. 17 The interaction effect plot for the crater size

Table 12 The ANOVA table for crater size based on the full factorial design

Source	*df*	SS	Contribution	MS	*F* value	*P* value
Model	53	2267.63	98.88%	42.79	180.01	0.000
Linear	7	2183.03	95.19%	311.86	1312.06	0.000
Coating	1	10.43	0.45%	10.43	43.87	0.000
Voltage	2	2042.96	89.08%	1021.48	4297.58	0.000
Capacitance	2	129.06	5.63%	64.53	271.49	0.000
rpm	2	0.58	0.03%	0.29	1.21	0.302
Two-way interactions	18	69.13	3.01%	3.84	16.16	0.000
Coating × voltage	2	3.16	0.14%	1.58	6.66	0.002
Coating × capacitance	2	2.34	0.10%	1.17	4.93	0.009
Coating × rpm	2	0.33	0.01%	0.17	0.70	0.498
Voltage × capacitance	4	61.45	2.68%	15.36	64.63	0.000
Voltage × rpm	4	0.45	0.02%	0.11	0.48	0.754
Capacitance × rpm	4	1.39	0.06%	0.35	1.46	0.220
Three-way interactions	20	12.18	0.53%	0.61	2.56	0.001
Coating × voltage × capacitance	4	3.84	0.17%	0.96	4.03	0.004
Coating × voltage × rpm	4	1.21	0.05%	0.30	1.27	0.286
Coating × capacitance × rpm	4	2.85	0.12%	0.71	3.00	0.022
Voltage × capacitance × rpm	8	4.29	0.19%	0.54	2.25	0.029
Four-way interactions	8	3.28	0.14%	0.41	1.73	0.100
Coating × voltage × capacitance × rpm	8	3.28	0.14%	0.41	1.73	0.100

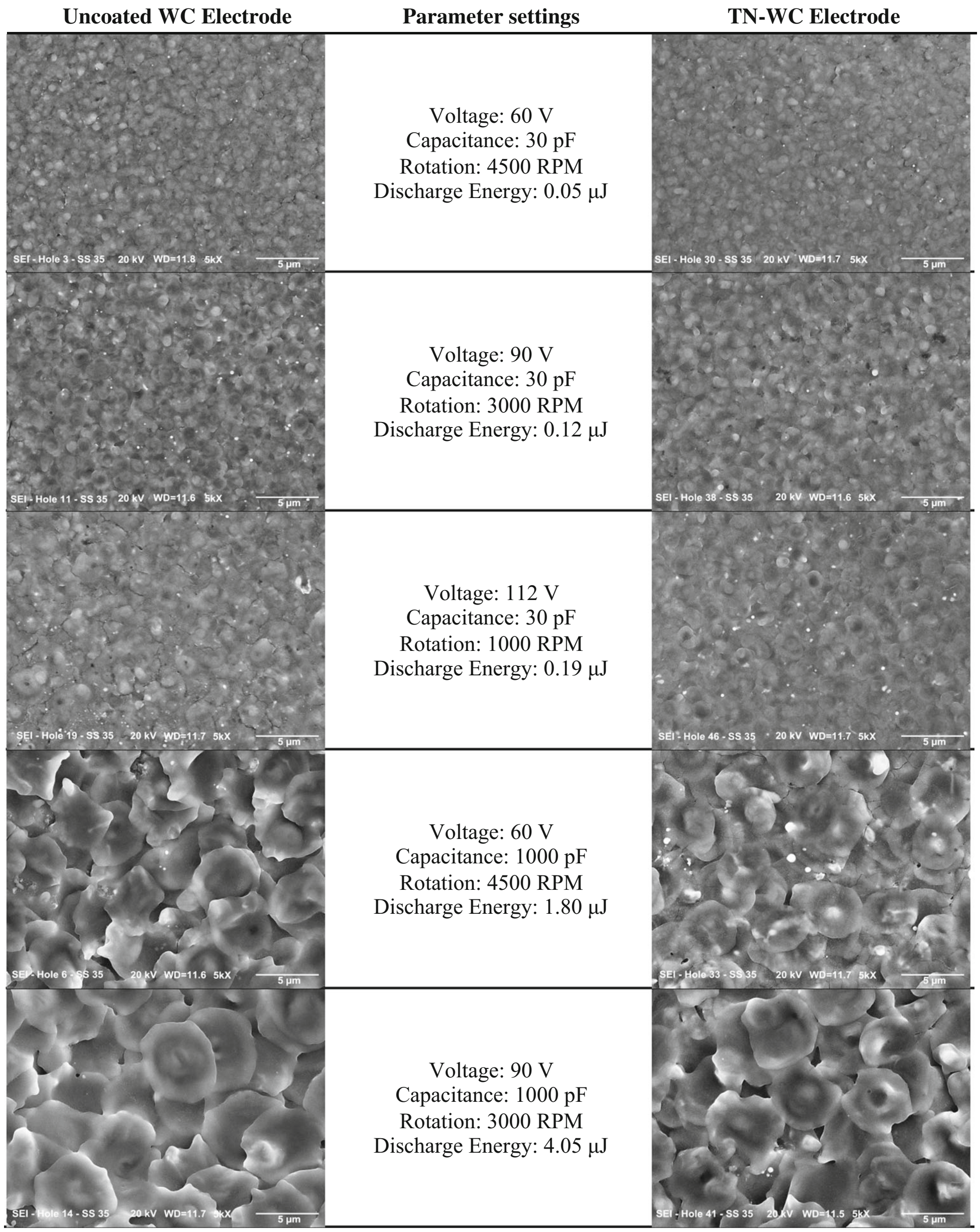


Fig. 18 SEM images—variation of crater sizes with the discharge energy (from 0.05 to 4.05 µJ)

studied by plotting these effects and conducting analysis of variance. Figure 23 displays the main effect plot for the micro-hardness. This plot shows the means of the micro-hardness for each level of process parameter. It was found that capacitance, voltage, and electrode rotational speed influenced the micro-hardness. The main effect of the TN coating on the micro-hardness was negligible. While increasing the capacitance resulted in the higher values of the micro-hardness, the voltage had the reverse effect. The effect of rpm was not consistent in different levels. However, the ANOVA (Table 15) demonstrated that the *P* value of the capacitance, the voltage, and the rpm were 0.000, which indicated that these main effects had a significant role in the resulting surface micro-hardness.

Figure 24 displays the interaction effect plot for the micro-hardness. Based on the plot, almost all parameters had the interaction effects. Moreover, the ANOVA (Table 15) shows that the interaction effects of these parameters were also significant. Although the capacitance had the most important effect on the micro-hardness with the contributions of 27.63%, other factors including three-way and four-way interactions had the considerable contributions on the resulting micro-hardness. The only exception was TN coating with the *P* value of 0.834, which was higher than 0.05. Therefore, the effect of TN coating was not statistically significant in determining the micro-hardness. From the ANOVA (Table 15), it was concluded that the capacitance was the most important parameter influencing the micro-hardness of machined surface.

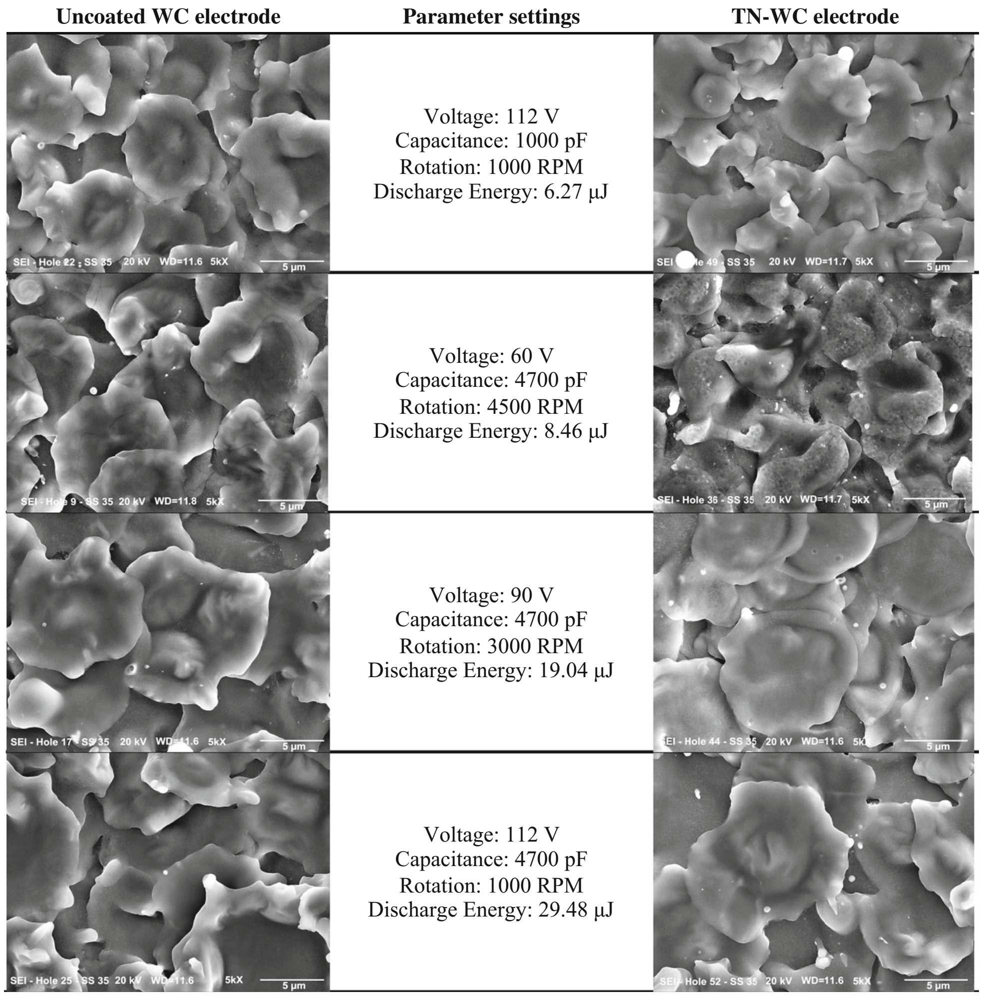


Fig. 19 SEM images—variation of crater size with the discharge energy (from 6.27 to 29.48 μJ)

3.5 Machining accuracy/overcut

The machining accuracy of the micro-holes was measured by the overcut of the micro-holes. The overcut of the micro-holes is defined as the gap between the hole and tool at each side and is measured by the (hole diameter − tool diameter)/2 [21]. In this study, the target hole dimension was same as the electrode diameter, which was 300 μm. Figure 25 shows the effect of voltage on the machining accuracy of the micro-holes. It was found that with the increase of gap voltage, the dimensions of the micro-holes were increased. This is due to the fact that during micro-EDM, the spark gap, i.e., gap between the electrode and the workpiece, increases with the increase of gap voltage [22]. The overcuts for the micro-holes machined using 60, 90, and 112 V at constant setting of 1000-pF capacitance and

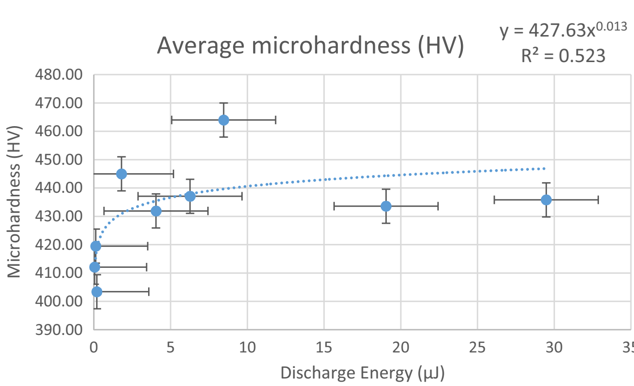


Fig. 20 The scatter plot—the discharge energy and the micro-hardness

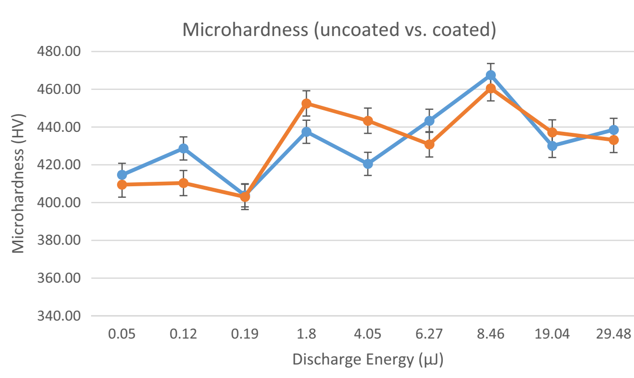


Fig. 21 The effect of TN coating on the micro-hardness (sorted by the discharge energy from low to high values)

Table 13 ANOVA for the micro-hardness: TN-coating effect

Summary						
Groups	Count	Sum	Average	Variance		
Uncoated	9	3884.5	431.6111	337.625		
Coated	9	3880.33333	431.1481	400.0656		
ANOVA						
Source of variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	0.964506	1	0.964506	0.002615	0.95985	4.493998
Within groups	5901.525	16	368.8453			
Total	5902.489	17				

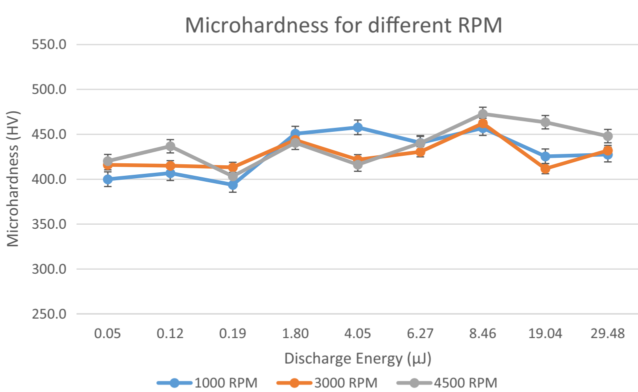


Fig. 22 The effect of the electrode rotational speed on the micro-hardness (sorted by the discharge energy from low to high values)

2500 rpm were found to be 9, 14.5, and 17.5 µm, respectively. The effect of capacitance on the machining accuracy of the micro-holes is presented in Fig. 26. It was found that with the increase of capacitance, the overcut of the micro-holes was increased. With the increase of capacitance, the duration of discharging increases in addition to increasing the discharge energy per pulse. As a result, the overcut of the micro-holes also increases [22]. The measured overcuts for the micro-holes machined at 30, 1000, and 4700 pF were found to be 10, 14.5, and 16 µm, respectively, where the voltage and electrode rotational speed were kept unchanged at 90 V and 2500 rpm. Figure 27 presents the effect of electrode rotational speed on the machining accuracy/overcut of the micro-holes machined at 60 V and 30 pF. It was found that unlike voltage and capacitance, no specific trend was followed with the increase of electrode rotational speed. It was found that both lower and higher settings of electrode rotational speed resulted in comparatively higher overcut. On the other hand, the machining conducted at moderately high setting of electrode rotational speed yielded lower overcut. This may be due to the fact that too low electrode rpm was not able to flush all the debris out efficiently from the machining zone, whereas too high electrode rpm resulted in turbulence in the machining zone causing movement of the tool electrode. The overcuts measured for 1000, 2500, and 4000 rpm were 20, 8.5, and 21 µm, respectively.

3.6 The optimal parameter setting

The combination of the optimal process parameter setting was identified to achieve the desired set of responses. Before finding the optimal values, the responses to be included in the analysis as well as their desired outcomes were defined. In this study, it was assumed that the important response variables were machining time, tool wear, crater size, and micro-hardness. The response optimizer of Minitab 17 was used to find the optimal parameters. With the confidence level of 95% for all intervals, the optimal values of micro-EDM process parameters were identified with their predicted responses. The optimal parameter setting and the estimated machining performance at that setting are shown in Table 16.

Table 14 ANOVA for the micro-hardness: electrode rotational speeds

Summary						
Groups	Count	Sum	Average	Variance		
1,000 rpm	9	3,859.5	428.8333	601.0938		
3,000 rpm	9	3,846.25	427.3611	284.1736		
4,500 rpm	9	3,941.5	437.9444	495.7934		
ANOVA						
Source of variation	SS	*df*	MS	*F*	*P* value	*F* critical
Between groups	591.5602	2	295.7801	0.642506	0.534782	3.402826
Within groups	11,048.49	24	460.3536			
Total	11,640.05	26				

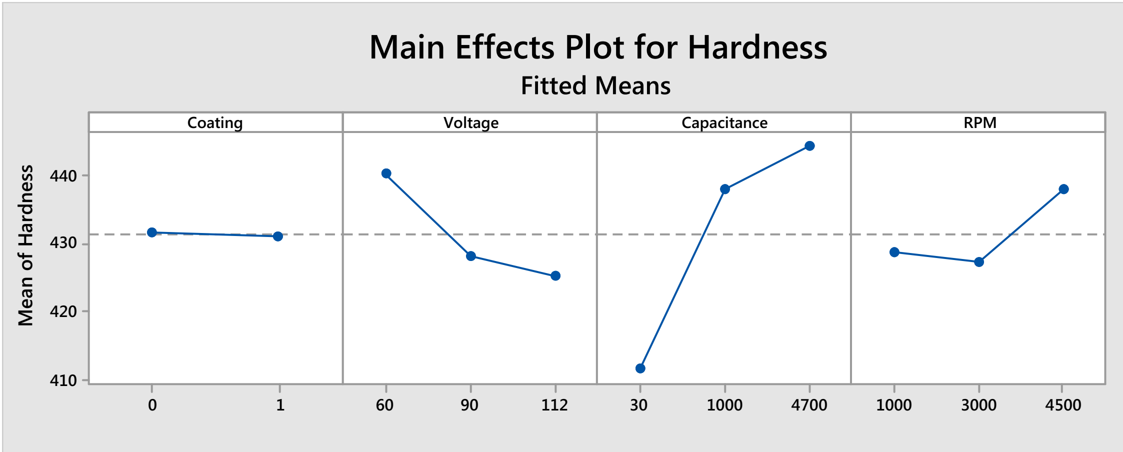


Fig. 23 The main effect plot for the micro-hardness

4 Conclusions

In this research, the RC-type micro-EDM machine was utilized to conduct an experimental study on the micro-EDM of Ti-6Al-4V alloy. The purpose of this study was to find out the relationship between the micro-EDM process parameters and the response variables, as well as to identify the optimal parameters. After analyzing the experimental data and evaluating the results, the following conclusions were drawn:

- The voltage was the most important parameter influencing both the machining time and the crater size. Increasing the voltage resulted in reduction in machining time, thus increasing the machining speed. However, the increase in voltage also resulted in broader crater size due to an increase in discharge energy. It was concluded that increasing the voltage had an adverse effect on the surface roughness. With the increase of the voltage, the spark gap between the workpiece and electrode was found to increase, which resulted in higher overcut of the micro-holes.
- The capacitance was the most important parameter for both tool wear and surface micro-hardness. Increasing the capacitance resulted in reduction of tool wear and increase in micro-hardness of the machined surface. It also

Table 15 The ANOVA table for the micro-hardness based on the full factorial design

Source	*df*	SS	Contribution	MS	*F* value	*P* value
Model	53	96,912	82.11%	1,828.5	9.35	0.000
Linear	7	42,925	36.37%	6,132.2	31.36	0.000
Coating	1	9	0.01%	8.7	0.04	0.834
Voltage	2	6,759	5.73%	3,379.7	17.29	0.000
Capacitance	2	32,608	27.63%	16,303.8	83.39	0.000
rpm	2	3,549	3.01%	1,774.7	9.08	0.000
Two-way interactions	18	25,753	21.82%	1,430.7	7.32	0.000
Coating × voltage	2	730	0.62%	365.1	1.87	0.159
Coating × capacitance	2	1,882	1.59%	941.1	4.81	0.010
Coating × rpm	2	1,240	1.05%	620.0	3.17	0.046
Voltage × capacitance	4	7,478	6.34%	1,869.6	9.56	0.000
Voltage × rpm	4	2,701	2.29%	675.3	3.45	0.011
Capacitance × rpm	4	11,721	9.93%	2,930.4	14.99	0.000
Three-way interactions	20	21,957	18.60%	1,097.9	5.62	0.000
Coating × voltage × capacitance	4	3,656	3.10%	914.0	4.67	0.002
Coating × voltage × rpm	4	3,715	4.84%	1,428.7	7.31	0.000
Coating × capacitance × rpm	4	7,563	6.41%	1,890.9	9.67	0.000
Voltage × capacitance × rpm	8	5,023	4.26%	627.9	3.21	0.003
Four-way interactions	8	6,276	5.32%	784.5	4.01	0.000
Coating × voltage × capacitance × rpm	8	6,276	5.32%	784.5	4.01	0.000

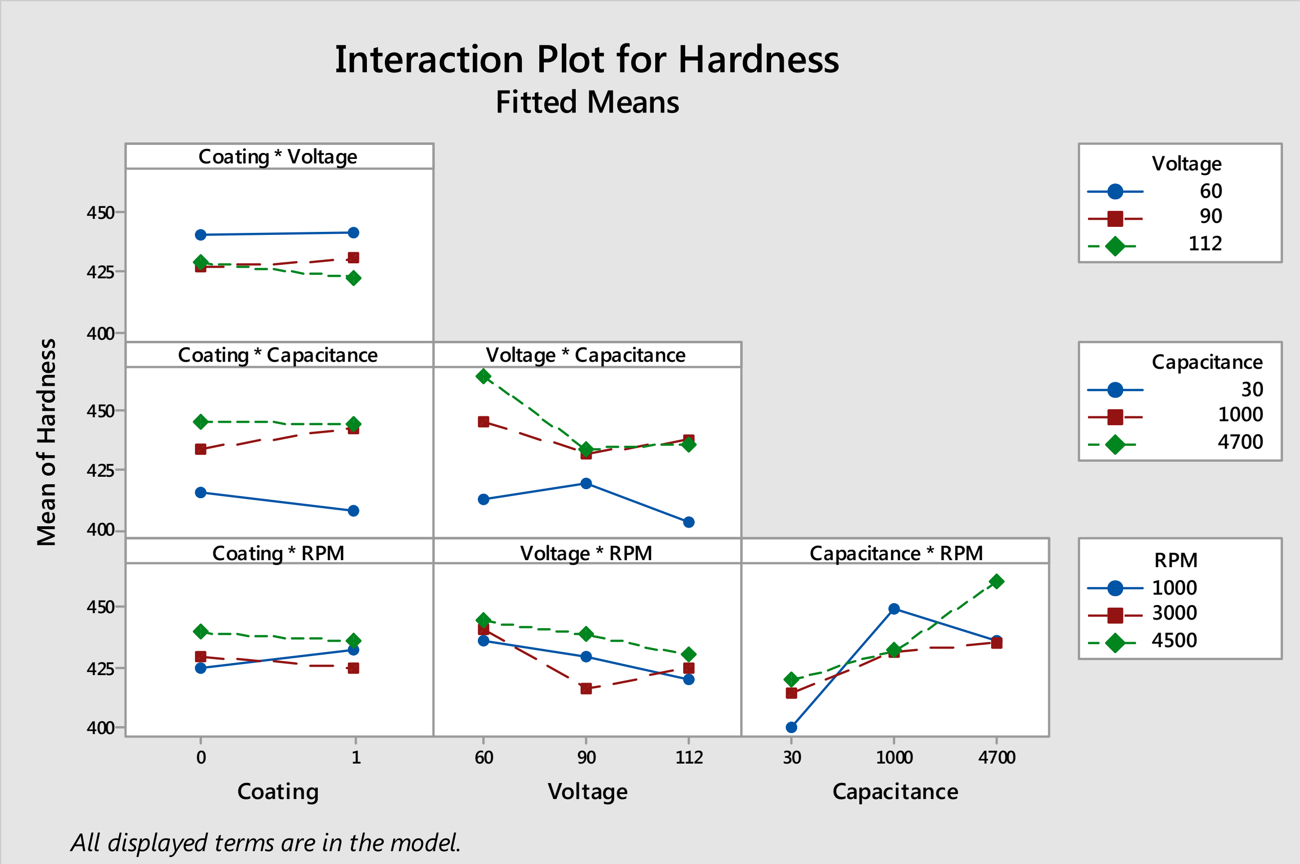
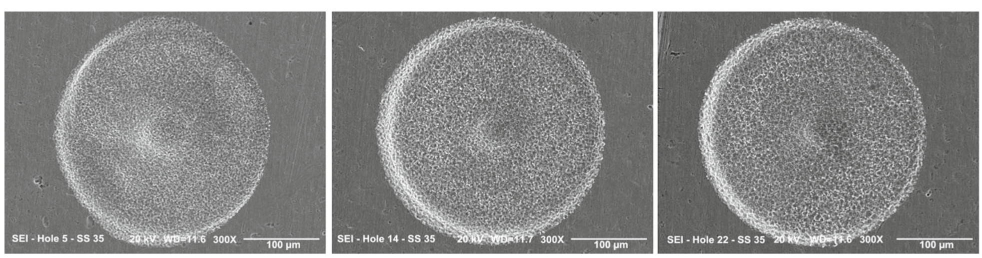


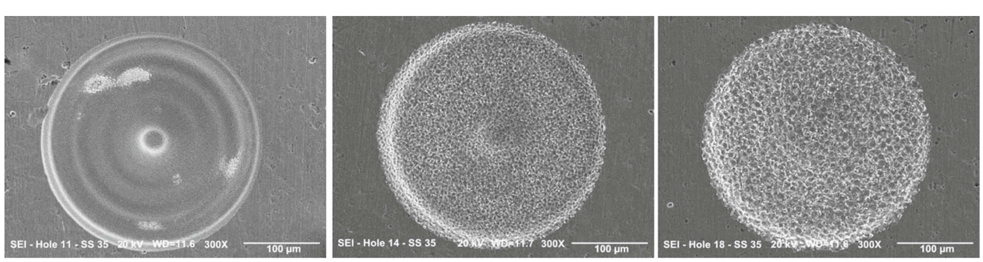
Fig. 24 The interaction effect plot for the micro-hardness

Fig. 25 Effect of voltage on the machining accuracy/overcut. **a** 60 V, Φ 318 μm, O.C. 9 μm. **b** 90 V, Φ 329 μm, O.C. 14.5 μm. **c** 112 V, Φ 335 μm, O.C. 17.5 μm (constant parameters capacitance = 1000 pF and electrode rotational speed = 2500 rpm)

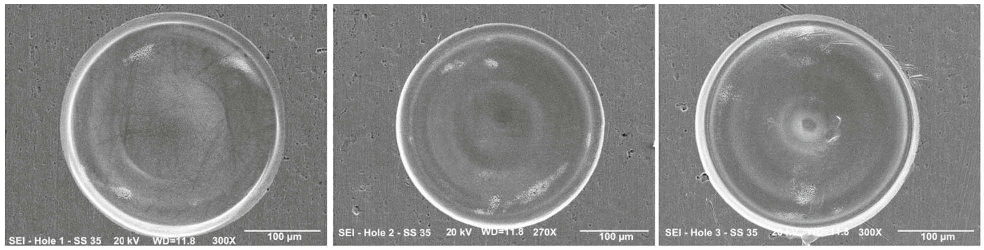


(a) (b) (c)

Fig. 26 Effect of capacitance on the machining accuracy/overcut. **a** 30 pF, Φ 320 μm, O.C. 10 μm. **b** 1000 pF, Φ 329 μm, O.C. 14.5 μm. **c** 4700 pF, Φ 332 μm, O.C. 16 μm (constant parameters voltage = 90 V and electrode rotational speed = 2500 rpm)



(a) (b) (c)



(a) (b) (c)

Fig. 27 Effect of electrode rotational speed on machining accuracy/overcut. **a** 1000 rpm, Φ 340 μm, O.C. 20 μm. **b** 2500 rpm, Φ 317 μm, O.C. 8.5 μm. **c** 4000 rpm, Φ 342 μm, O.C. 21 μm (constant parameters voltage = 60 V and capacitance = 30 pF)

Table 16 The optimal values of the process parameters and their predicted responses

Optimal parameters				Machining time fit	Tool wear (Δ*l*) fit	Crater-size fit	Hardness fit
Electrode	Voltage	Capacitance	rpm				
TN-WC	60	4700	3000	237 s	3 μm	1.26 μm	475.5 HV

caused a decrease in the machining time due to increase in discharge energy. The overcut of the micro-holes was also found to increase with the increase of capacitance, thus affecting the machining accuracy of the micro-holes.

- The effect of TN coating was not very significant. There was slight reduction in the machining time and crater sizes when the WC electrode with TN coating was used. However, from the statistical point of view, those effects were not significant. The slight reduction in machining time with TN-coated carbide tools compared to uncoated carbide tools might be associated with the increased electrical conductivity of the TN coating, which could result in faster transfer of current between the tool and workpiece.
- The effect of the electrode rotational speed was not statistically significant. It was found that the machining time and surface micro-hardness increased slightly at lower rpm, mostly due to lack of flushing effectiveness. However, a moderately higher setting of rpm was found to provide stable and improved machining performance with no further improvement of machining performance with increasing rpm. This might be due to the reason that at higher electrode rotational speed, the machining stability suffered due to the turbulence created in the machining zone.
- For RC-type micro-EDM, the discharge energy was found to be the most important indicator/parameter influencing the machining performance directly. The machining time, crater size, and tool wear followed excellent trends with good fit of data (R-squared value of higher than 0.9), when plotted against the discharge energy. Considering the effects of all parameters, the optimum parameters for micro-EDM of Ti-6Al-4V identified by the response optimizer of Minitab 17 were TN-coated WC tool, 60 V, 4700 pF, and 3000 rpm.

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