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Experimental Investigations on Cutting Rate and Kerf Width on Wire-Electro Discharge Machining of Silicon Nitride – Titanium Nitride Ceramic Composite

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Abstract

The growing benefits of ceramic composites in their usages in automotive, Bio medical implants, nuclear, and aircraft industries make them the most sought-after significant material. However, cutting these composites with traditional machining is very challenging. The non-traditional machining process like electric discharge machining (EDM) are crucial to machine them. Wire EDM is equipped to machine any kind of material, regardless of how it naturally behaves. Using a coated copper electrode, the current work focusses on investigation of the effects of Wire EDM parameters on Si_3N_4-TiN ceramic composite. The major machining parameters are servo voltage, short pulse on time, and pulse on time, which were varied over five levels, whereas cutting rate and width of cut are considered as the machining performance characteristics. Using Response Surface Methodology (RSM) that is based on Design of Experiments (DOE) the distinctive characteristics of the WEDM process are investigated. Empirical models have been created for cutting rate and kerf width. According to the findings, the servo voltage is the second most important component, after the pulse-on time.

Keywords: Cutting Rate, electrode, Kerf Width, Si_3N_4-TiN, RSM, Wire-EDM.

Introduction

The field of material science has advanced significantly in previous few years, particularly in the areas of ceramic composite materials. Ceramic composite finds their application in various diversified fields such as Biomedical implants, nuclear reactor devices, manufacturing of high-temperature applications in an aircraft industry and many more. These composites possess high hardness and strength, therefore rendering it difficult to machine it by conventional method thereby making it difficult to cut complex shapes and contours in it (1).

When machined conventionally, they leave the surface with cracks and voids, due to their poor machinability, thus causing excessive tool wear. Previous research indicates that this type of composite material is appropriate for the unconventional machining process (2). As post-machining procedures may be required for traditional machining processes, raising the material's machining cost. Electrically conductive ceramic-based composites are very difficult to machine conventionally because of the strong reinforcing particles; a greater force is needed to de-bonds the particles. However, this might cause the machined materials to retain some residual stress (3).

Therefore, non-traditional machining techniques are employed in place of traditional machining techniques. Because it facilitates the machining of complex shapes on the component to be machined, the electric discharge machining (EDM) process is selected as an efficient technique for machining electrically conductive ceramic-based composites (4). Additionally, after machining, it leaves no residual stresses on the material. There are many non-traditional methods available for machining ceramic-based composites, and EDM is one of those methods that is both economical and energetic. Additionally, components that are challenging to machine using non-traditional machining techniques can be efficiently machined using the EDM process (5), this study concentrates more on unconventional methods for shaping ceramic-based composites (6).

The majority of ceramic materials that have been

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produced recently can be broadly categorized as either conductive or non-conductive. Zirconia (ZrO2), silicon carbide, aluminum oxide (Al_2O_3), and silicon nitride (Si3N4) are examples of common non-conductive ceramics. By adding conductive particles to the material, such as TiC, TiN, CaO, Si, TiB_2, or B_4C, Si_3N_4, Si_3 N_4+TiN, Si_3N_4+TiC, Al_2O_3, Al_2O_3 +TiC, Al_2O_3 +TiN, ZrO_2 +CaO, ZrO_2 +Y_2O_3, and TiN, ceramic conductivity can be attained (7).

Si_3N_4-TiN composites are used in aerospace applications due to its exceptional properties like higher hardness at elevated temperatures. Shaping them thorough WEDM can lead to generating intricate contours, and enhance their performance, while increasing the life span of aerospace components by improving their reliability. It is further used in biomedical implants, thermal generator components to name a few (7).

Si_3N_4-TiN composites can endure mechanical properties at elevated temperatures, leading to less wear and tear and increasing the reliability of the products.

EDM is an ideal candidate for those materials possessing extremely low electrical conductivity. It is not impacted by the mechanical properties of the material and can create extremely intricate shapes. These advantages have stimulated EDM research into conductive ceramic composite materials. When using EDM, the major machining parameters selected has a profound effect on both surface quality and machining performance (8).

Input variables like pulse current (I), voltage (V), pulse on time (μs), and pulse off time (μs), with non-electrical variables like dielectric, tool rotation, and workpiece rotation, are all the essential parameters that affect machining performance (9).

Si_3N_4-TiN intermetallic ceramic composite has maximum toughness, lower thickness, high hardness, higher electrical conductivity, higher temperature creep resistance, and lower temperature malleability, it is generally used in the construction of gas turbine motors, contemporary gas burners, diesel engine glow plugs, and power generation components for aerospace applications and for fabrication of Biomedical implants (10).

The study conducted by Srinivasan et al., (11) used response surface methodology and experimental software design to examine the performance parameters of Si_3N_4-TiN with plain copper electrode during EDM machining. They found that when the EWR decreased, the MRR increased, and they came to the conclusion that amongst the Pulse on time, voltage and current, are the most influenced parameter in the EDM of Si_3N_4-TiN ceramic composites is the current.

In order to examine the surface roughness, wear rate, and microhardness, Srinivasan et al., (12) experimented with pulse on time, pulse off time, spark gap voltage, peak current and wire feed rate using copper wire material on ceramic composite of Si_3N_4-TiN. The investigation's findings demonstrate that longer pulse durations and higher peak currents were found to have an impact on MRR.MRR and TWR are significantly impacted by parameters like pulse on time. Voltage and current with current being the most important parameter and the other parameters being negligible.

During his findings for WEDM of Si_3N_4-TiN ceramic composite, Farooqui et al., (13) optimised the process parameters for cutting rates and width of cut, and the investigation led to a conclusion that current is the most significant factor amongst all the other performance parameters effecting the cutting rates and kerf width.

Using Taguchi and GRA for the square copper electrode during his studies, Selvarajan et al., (14) employed multi parametric optimization on performance parameters like pulse on time, pulse off time, and current and discovered that current was the most important parameter. And concluded that factors like pulse on duration and current cause MRR to rise and EWR to fall. The results of the investigation obtained by Selvarajan et al., (15) showed that the material removal rate and surface roughness with graphite electrode was higher than that of copper electrode. They also concluded that the rate of material removal was higher for copper in relation to time duration, while the MRR for graphite electrode increased with current. where voltage, current, and pulse duration are important variables.

By utilizing a square-shaped copper electrode along with (RSM), Selvarajan et al., (16) optimized the performance parameters for Si_3N_4-TiN, the investigation led to a discovery that current was the key parameter. They concluded that factors like pulse on duration and current cause MRR to rise and EWR to fall. High tool wear rate, microcracks, voids, pit formation and embedded fractured particles on the machined surface are the challenges encountered during conventional machining of ceramic composite.

WEDM is a non-contact machining process, which completely reduces tool wear, can be used for shaping non conducting materials like ceramics, at the same time it can machine materials possessing very high level of hardness and can machine complex geometric contours with equal ease.

Zinc coated copper electrode is used for machining Si_3N_4-TiN ceramic composite, which enhances the cutting rates significantly while maintaining the kerf width in an appreciable range. This is significant from maintaining higher levels of tolerances.

The results can help in improving productivity by having better cutting rates, kerf width and surface finish, leading to improved quality and reducing the machining costs. It will further ensure that better dimensional accuracy leading to higher productive life of the components.

Recent researches on wire EDM on ceramic composites offer a deep insight into optimization techniques using tools like ANN, Genetic algorithms, dealing with different composite materials like Al2O3, ZrO2, sailon and Al_2O_3 +TiC, Al_2O_3 +TiN, ZrO_2 +CaO, ZrO_2 +Y_2O_3 . which signifies the importance of WEDM as a crucial technology in machining of advance materials like ceramic composites

The machining quality greatly influences the performance of material in applications. These challenges can be addressed by wire EDM. The literature indicates that there is a dearth of knowledge regarding the performance measures like cutting rates and kerf during wire-EDM with a coated copper wire for a composite containing 35% TiN in Si_3N_4 ceramic composite.

This study examines how the critical parameters like servo voltage, pulse on time duration, and short pulse on time duration impacts the cutting rate and kerf. This study aims to investigate through experimentation how process parameters, both electrical and non-electrical, affect three key performance measures: surface roughness kerf width, and cutting rate.

Methodology

The experiments in this study were planned using Box and Hunter's experimental design technique by applying Myers and Montgomery's (17) central composite experimental design (CCD), it was possible to reduce the number of experiments without sacrificing accuracy or reliability. The present investigation employed Servo voltage (V), pulse on-time (Ton), and short pulse on-time (Tac) are the three input parameters for which experiments were conducted using Response Surface Methodology (RSM)s, Central Composite Design (CCD) technique.

For every parameter, five levels were selected. Cutting rate (mm^2/min), kerf width (mm), and surface roughness (Ra, µm) were the chosen responses as illustrated in Table 3. The RSM calculates the value of responses at each point within the volume bounded by the CCD curvature. Three input parameters make up the design: short pulse on-time, pulse on-time, and servo voltage.

A five-axis CNC (Charmilles Technology) Robofill 300 Wire Electrical Discharge Machine was used for the experiments. A zinc coated copper wire electrode of 0.25mm diameter was used. Si_3N_4-TiN composite, which has about 35% of TiN suspended in the matrix, was the work material used in the experiments.

The dielectric used was deionized water, having an electrical conductivity of 25µS/cm. Based on the preliminary experiments, the input parameters along with their levels have been determined. The work piece properties are highlighted in Table 1. The machining factors and their levels are mentioned in Table 3.

The current intensity at the spark's initiation is known as the ignition pulse current. There is no significant effect on the process parameters by it. Changes in it cause the work piece and the wire electrode to repel one another, leading to wire shifting or breakage. Keeping this in view, it was kept constant at 16A.

Gap contamination was found to have a negative impact on flushing pressure at lower flushing pressure levels during the preliminary and screening tests. As a result, fixing the flushing pressure at a higher level of pressure was decided upon for the current studies.

Severe wire breakages during one-factor-at-a-time experiments prevented this material from being machined beyond 120V. Furthermore, because of severe wire breaks, there is a limited range of parameters that can be changed simultaneously with voltage. Additionally, the process becomes unstable due to variations in the generator's hidden parameters brought on by the voltage change. As a result, an 80 V open circuit voltage was maintained consistently. Wire speed and maximum wire feed have also been set at suitable levels to prevent wire breakages during the experiments, based on the preliminary results and our WEDM experience as stated in Table 2.

Table 1: The Properties of Si_3N_4-TiN Ceramic Composite Work Piece

Sr.No	Properties	Units	Si_3N_4-TiN
1	Youngs Modulus of Elasticity	(GPa)	341
2	Hardness	(GPa)	90.5
3	Fracture Toughness	(K1C – MPa m1/2)	5.7
4	Co efficient of thermal Expansion	(K-1)	5.6 x 10– 6
5	Thermal Conductivity	(W/m°K)	19.1
6	Electrical Resistivity	(Ωm)	7.24 x 10– 6
7	Density	(g/cc)	4.01
8	Poisson Ratio		0.31
9	Flextural Strength	(MPa)	835 ± 116.0
10	Grain Size of TiN	µm	3 to 5

Table 2: Details of the Experiment (Fixed Factors)

Machining parameters	Fixed levels
Work piece height	10 mm
Length of cut	15 mm
Angle of cut	Vertical
Location of work piece	Center of the table
Work piece material	Si_3N_4-TiN*
Temporary Reduction in frequency (FF)	50
Duration of pulse off time	15 µs
Ignition Pulse current (IAL)	16 A
Open circuit voltage (V)	-80 V
Strategy (ST)	1
Dielectric	Deionized water, 15µS/cm
Dielectric Temperature	22 C

**Rauschert GmbH ceramic composite*

Table 3: Machining Factors and Their Levels

Variables	Symbols	Units	Levels				
			-2	**-1**	**0**	**1**	**2**
Pulse on duration	Ton	(µs)	0.4	0.6	0.8	1	1.2
Short pulse duration	Tac	(µs)	0.2	0.2	0.4	0.6	0.6
Servo Voltage	Aj	V	50	50	60	70	70

The workpiece's height measured 10 mm, and the length of cut was measured at 15 mm. Cutting speed in mm^2/min, kerf width in mm, and surface roughness in µm were the measured responses. profile projector was used to measure the kerf width. Mitutoyo surface roughness tester was used for measurement of the surface roughness, and the cutting speed was noted from machine's display. The JEOL JSM-6380A analytical SEM was used to carry out the SEM investigations.

Results and Discussion

The impact of input parameters on responses based on analysis, are presented along with discussion in this section.

Regression analysis has been performed for the response variable modeling using minitab, a commercially available program. The effectiveness of the created models has been evaluated, and the effects of input parameters and their interactions with response variables have been examined, using analysis of variance (ANOVA) (18). ANOVA is

used to confirm the developed models' significance. Verifying the developed model's significance is essential to dictate the importance of the input parameters, interactions, and quadratic terms (19).
Table 4 displays the levels and ranges of various input and output parameters used to conduct the experiment.

The impact of input parameters on Cutting Rate (CR): The results of experiments are analysed using Analysis of Variance (ANOVA), from Table 5. The servo voltage, pulse on-time, and pulse off-time were found to have a significant impact on the cutting rate based on ANOVA. According to the F-test, Servo voltage followed by pulse on-time was the significant input parameter for cutting rate.

Table 4: Experimental Results of Cutting Rate and Kerf for the Responses

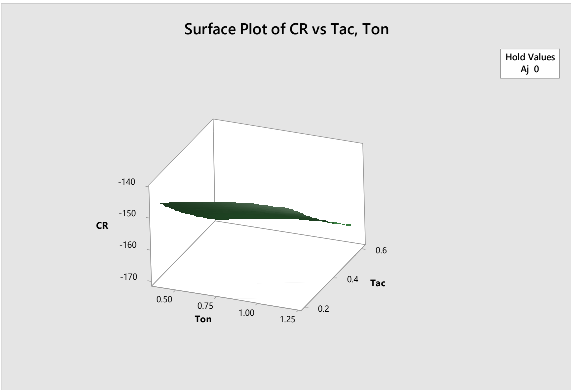
Sr. No	Pulse on duration Ton (μs)	Short pulse duration Tac (μs)	Servo voltage Aj	Width of cut kerf mm	Cutting rate mm^2/min
1	0.6	0.2	50	0.3420	8.909
2	1	0.2	50	0.3600	10.318
3	0.6	0.6	50	0.3560	5.227
4	1	0.6	50	0.3433	5.500
5	0.6	0.2	70	0.3640	2.591
6	1	0.2	70	0.3613	3.591
7	0.6	0.6	70	0.3400	2.591
8	1	0.6	70	0.3573	4.000
9	0.4	0.4	60	0.4200	3.560
10	1.2	0.4	60	0.4300	8.460
11	0.8	0.2	60	0.4100	7.840
12	0.8	0.6	60	0.4200	6.250
13	0.8	0.4	50	0.3193	5.318
14	0.8	0.4	70	0.3520	3.318
15	0.8	0.4	60	0.3700	7.020
16	0.8	0.4	60	0.3700	9.070
17	0.8	0.4	60	0.3600	9.160
18	0.8	0.4	60	0.3900	8.860
19	0.8	0.4	60	0.3880	8.790
20	0.8	0.4	60	0.3900	8.875

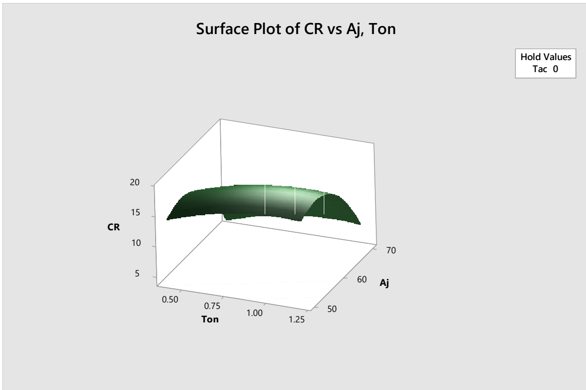
A response surface model for cutting rate has been developed based on the outcomes of the planned experiments. The R-sq value of 98.72 for cutting rate, indicates high predictability of the response surface model for cutting rate. The *p*-values observed are significant and acceptable. The lack of fit is noted to be insignificant, highlighting a good compatibility between experimental and model predictions.
The empirical Equation for cutting rate is as shown below in equation 1:

$$\text{Cutting Rate} = -137.0 + 18.22\,Ton - 79.98\,Tac + 5.327\,Aj - 7.75\,Ton*Ton + 24.83\,Tac*Tac - 0.04828\,Aj*Aj + 1.12\,Ton*Tac - 0.034\,Ton*Aj + 0.824\,Tac*Aj \quad [1]$$

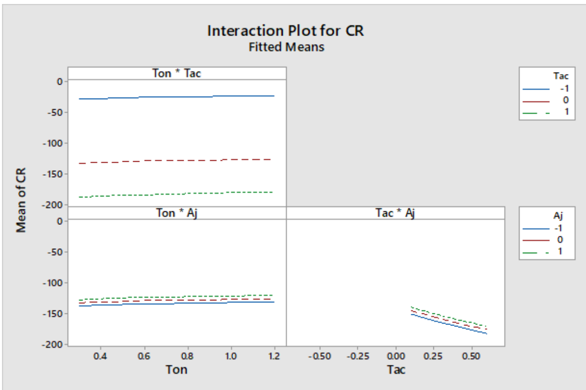
Table 5: Analysis of Variance for Cutting Rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	158.319	17.5910	68.54	0.000
Linear	3	46.718	15.5726	60.67	0.000
Ton	1	1.570	1.5697	6.12	0.039
Tac	1	18.444	18.4437	71.86	0.000
Aj	1	44.446	44.4456	173.17	0.000
Square	3	68.431	22.8103	88.87	0.000
Ton*Ton	1	2.484	2.4837	9.68	0.014
Tac*Tac	1	2.310	2.3097	9.00	0.017
Aj*Aj	1	51.577	51.5765	200.95	0.000
2-Way Interaction	3	17.974	5.9913	23.34	0.000
Ton*Tac	1	0.011	0.0105	0.04	0.844
Ton*Aj	1	0.024	0.0240	0.09	0.768
Tac*Aj	1	14.358	14.3585	55.94	0.000
Error	8	2.053	0.2567		
Lack-of-Fit	3	1.703	0.5678	8.11	0.023
Pure Error	5	0.350	0.0700		
Total	17	160.373			





(A) (B)



(C) (D)

Figure 1: (A) surface plot for Tac, Ton Vs CR, (B) surface plot for Aj, Ton Vs CR, (C) Main effect plot for CR, (D) Interaction plot for CR.

Figure 1(A) and 1(B) Depicts the impact of servo voltage and pulse on time on cutting rates, it is observed that the cutting rates at low values of servo voltage and on time duration are in the range of 5.22 mm^2/min to 10.38mm^2/min, on increasing the value of servo voltage the cutting rates fall further in the range of 3.59 mm^2/min to 2.12mm^2/min.

It is noted that when the servo voltage increases, the cutting rate decreases, further, from Figure 1(C) and 1(D) it is observed that the cutting rate value falls as the servo voltage value rises. It was discovered that the value of the cutting rate increased as pulse one time increased. The spark gap is directly impacted by the servo voltage (20-21), a rise in servo voltage causes the spark gap to increase and the concentration of spark discharge in the machining direction to decrease, which lowers the cutting rate. The material removal rate increases due to increase in discharge energy and pulse on time; that is, as the discharge energy rises, extra material is removed, increasing the cutting rate.

Figure 2 highlights the effects of short pulse on time and voltage on cutting rates. As servo voltage increase from Figure 2(A) and 2(B), the cutting rate is decreased and the wire forward feed speed is adjusted in tandem with a rise in servo voltage. A large servo voltage may cause the wire to retract in order to preserve the appropriate gap, which would lower the cutting rate. The cutting rate is relatively low due to a decrease in discharge frequency caused by an increased short pulse on time, from Figure 2(C) and 2(D). The cutting rate is very low at higher servo voltage and higher short pulse on time values. It is clear that as the pulse on time rises, the cutting rate increases and decreases as the short pulse on time increases. It's interesting to note that cutting rate was significantly impacted by the interaction between the short pulse on time and servo voltage.

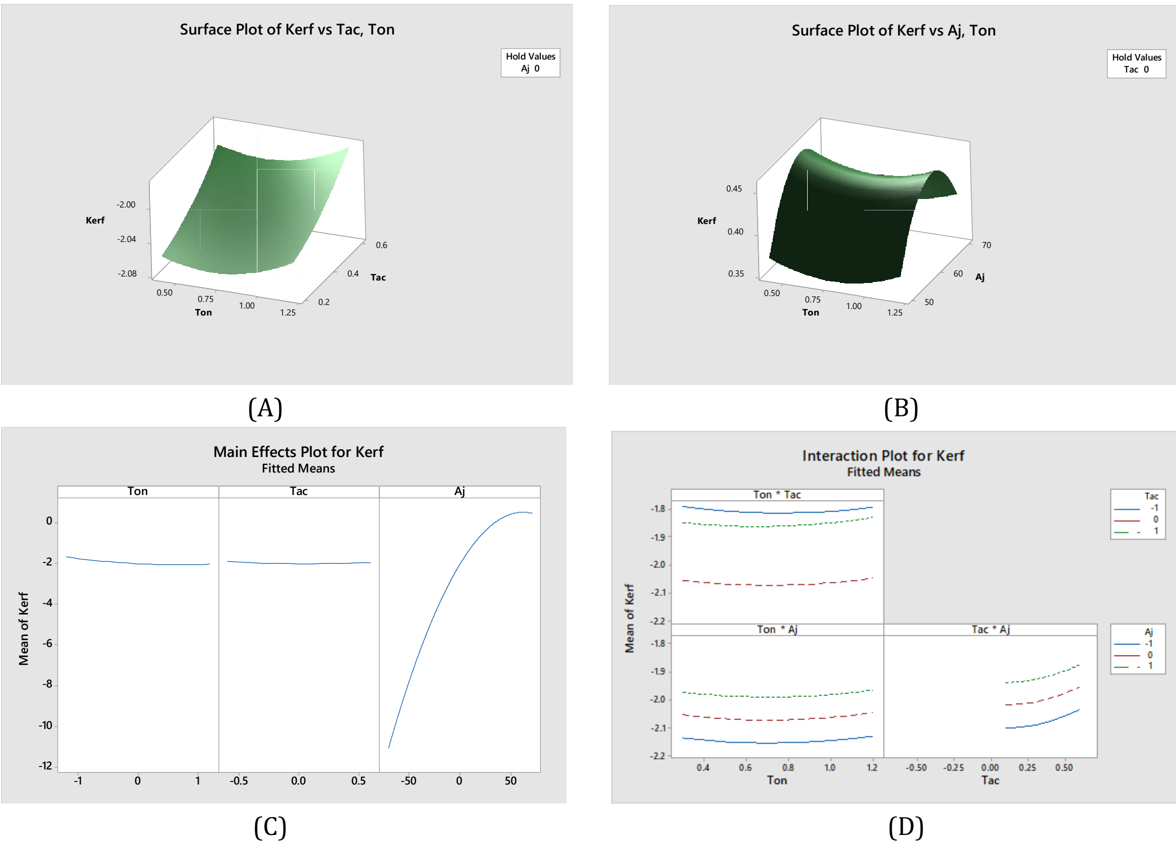


Figure 2: (A) surface plot for Tac, Ton Vs kerf, (B) surface plot for Aj, Ton Vs kerf, (C) Main effect plot for kerf, (D) Interaction plot for kerf

The impact of input parameters on Kerf Width (width of cut): In Table 6 the kerf width ANOVA is displayed. The kerf is crucial since it establishes the final part's dimensional accuracy. A computer-controlled positioning system continuously maintains the gap between wire and workpiece, which normally ranges between 0.025mm - 0.075 mm. It has been discovered that the two most important input parameters on the kerf width are servo voltage and pulse on-time.

The R-sq value of 99.02 signifies that the model posses high predictive capabilities. Regression Equation for kerf width is as given below in equation 2:

$$Kerf = -2.018 - 0.1505\,Ton - 0.0324\,Tac + 0.08223\,Aj + 0.1060\,Ton*Ton + 0.2336\,Tac*Tac - 0.000669\,Aj*Aj + 0.0119\,Ton*Tac - 0.00032\,Ton*Aj - 0.00249\,Tac*Aj \quad [2]$$

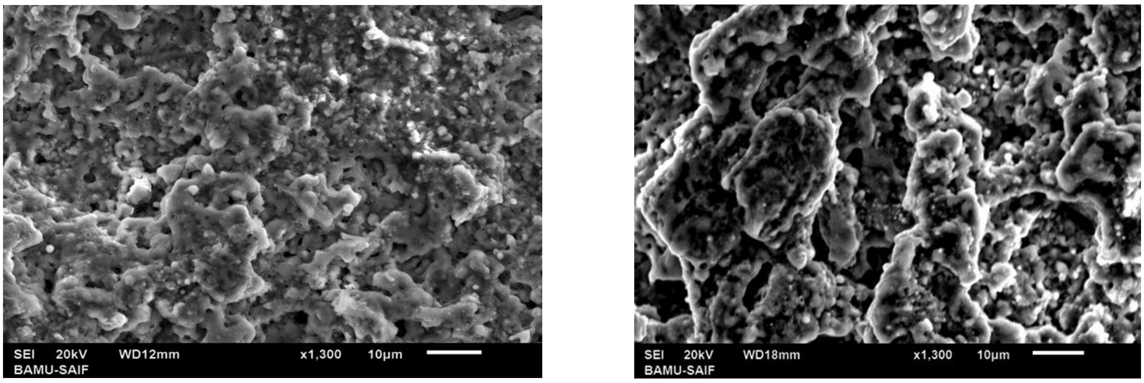
Table 6: Analysis of Variance for Width Of Cut

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.018701	0.002078	89.39	0.000
Linear	3	0.014421	0.004807	206.81	0.000
Ton	1	0.000107	0.000107	4.61	0.064
Tac	1	0.000003	0.000003	0.13	0.727
Aj	1	0.010592	0.010592	455.68	0.000
Square	3	0.015236	0.005079	218.49	0.000
Ton*Ton	1	0.000464	0.000464	19.98	0.002
Tac*Tac	1	0.000204	0.000204	8.80	0.018
Aj*Aj	1	0.009907	0.009907	426.23	0.000
2-Way Interaction	3	0.000143	0.000048	2.05	0.185
Ton*Tac	1	0.000001	0.000001	0.05	0.826
Ton*Aj	1	0.000002	0.000002	0.09	0.767
Tac*Aj	1	0.000131	0.000131	5.63	0.045
Error	8	0.000186	0.000023		
Lack-of-Fit	3	0.000085	0.000028	1.41	0.344
Pure Error	5	0.000101	0.000020		
Total	17	0.018887			

Figure 2(A) and 2(B) highlights the impact of voltage and pulse on time on kerf. Larger kerf widths were observed at high pulse on time levels. It is discovered that the influence of the pulse on-time outweighed the servo voltage. Greater current is supplied by longer on times, which increases the energy in the spark gap. Consequently, as on-time increases, the gap widens. The p values observed are significant and acceptable.

The kerf width was noted to be minimum at the mid-level of servo voltage and pulse on time from Figure 2(C) and 2(D). It was discovered that the kerf width was lowest at the midpoint of the servo voltage and pulsed promptly. The material removal rate increases with an increase in pulse on-time, creating a wider gap between the workpiece and wire (22). In order to provide the discharge voltage at the servo voltage's set value, the wider spark gap caused by the higher servo voltage causes the gap voltage to be adjusted. It is generally accepted that a wider cut results from a higher peak current (23), however, the thermal and electrical conductivity of the ceramic matrix or TiN particle in the wire's path may also influence the width of the cut if ceramic particles are present.

Machined Surfaces: Using scanning electron microscopy, the cross-section and machined surfaces have been evaluated. Furthermore, an effort was made to look into the effects of other input parameters and pulse energy (on-time) on surface morphology. Figure 3(A) and 3(B). The topography of machined surfaces of Si_3N_4-TiN ceramic composite has been studied.



(A) (B)

Figure 3: Depicts the SEM images of the machined surfaces: (A) at low level of pulse on time, (B) at high level of pulse on time. Gallery of SEM micrographs. Legend: 3(A) sample 301, 1300× (the marker is 10 μm wide); 3(B) sample 302, 1300× (the marker is 10 μm wide)

The surface machined was observed to be made up of pores, voids, and redeposited debris. It seemed that the servo voltage had little effect on the machined surfaces' surface topography. It is observed that the surface roughness Ra values correlate with the SEM micrographs.

However, it was discovered that the surface topography was greatly influenced by the on-time. When compared to short pulse on-times, the craters' volume and depth seemed to be greater and more substantial at higher on-time levels.

The experimental WEDM's pulse on-time determines the peak current's rise and, to some extent, its magnitude at fixed voltage, The current slope was fixed at 400 (A /μ s). As a result, the peak current magnitude varies in relation to the pulse on-time in accordance with the current rise slope. Hence, the discharge energy and on-time duration are directly proportional. The effects of on-time are visible in the SEM images.

Conclusion

The experimental investigations allow for the following conclusions to be made:

It is observed that servo voltage, short pulse on time, and pulse on time all had a profound impact on the cutting rate. Pulse on-time was noted to have an impact on surface roughness; where as other factors did not significantly affect it. Kerf width is influenced by servo voltage and pulse on-time. The kerf width is observed to be minimum at the middle values of the servo voltage range and lower pulse on-time. This is because there is less material removal at lower pulse on-time values because the rate of discharge energy formation is lower. Response surface models were created for cutting rate and kerf width. The R-sq values for these responses were 98.72 and 99.02 for cutting rate, and kerf width respectively. surface topography has been found to be significant effected by pulse on time, as observed through SEM images. The WEDM is highly promising in shaping of silicon nitride-titanium nitride ceramic composites. Optimization of the WEDM process for machining of the silicon Nitride- Titanium Nitride ceramic composite can be the next stage of the investigation.

Abbreviation

CR: Cutting rate

Kerf: Width of cut

Aj: Servo Voltage

Ton: Pulse on duration

Tac: Short Pulse on duration

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Author Contributions

M.N. Farooqui, conceptualized the study as well as collected and analysed the data and drafted the manuscript; A.S. Gore and N.G. Patil critically reviewed the manuscript.

Conflict of Interest

There is no conflict of interest between the authors, regarding the publication of this article.

Ethics Approval

This research article is the authors' own original research work, this has not been previously published elsewhere. This research article is not currently being considered for publication elsewhere. All data and sources used are properly cited.

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