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Investigation into Optimizing of Machining Parameters using RSM for Si_3N_4 -TiN Ceramic C omposites by WEDM

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Abstract

Objective: To maximize the cutting rates and to minimize and width of cut (Kerf) by optimizing the process parameters for wire EDM machining of Si_3N_4-TiN ceramic composite utilizing zinc coated brass wire optimizing the process parameters by applying Response Surface Methodology using Central Composite Design Technique. **Methods:** The input parameters, namely, peak current, short pulse duration, and pulse on time duration were varied over five different levels, in order to conduct the studies. The distinctive response characteristics, such as cutting rates and width of cut, are investigated, and optimized using Response Surface Methodology (RSM), which is based on Design of Experiments (DOE). ANOVA was applied to both predictive modeling and the identification of significant variables in order to assess the effectiveness of the model. In the experiments, a coated brass wire electrode was employed in the center composite design. **Findings:** Comparing the cutting rates with a plain brass electrode, the increases are 4.39% and 16.67%, respectively. The pulse-on time and pulse current are recognized as the two most crucial input parameters; cutting rate rises with increasing current. A coated brass wire with negative tool polarity achieved a maximum cutting rate of 69.72 mm^2/min at a peak current of 320A, 1.2 μs of on time pulse duration, the ideal Kerf of 0.35mm was obtained. The % error of RSM predicted and actual is 5.36% for cutting rate and 1.05% for Kerf. **Novelty:** There is no literature available on the machining of Si3N4-TiN using coated brass wire, for Kerf width and cutting speeds. The zinc-coated brass wire electrode improves the cutting rates and reduces the Kerf significantly for Si_3N_4-TiN ceramic composite.
Keywords: Si_3N_4-TiN, CR, Kerf, RSM, ANOVA

1 Introduction

Ceramic composites are excellent choices for high temperature applications because of their exceptional strength and hardness. As a result, complex shapes cannot be machined in them using traditional machining techniques[1]. The great majority of ceramic matrix composite materials are typically non-conductive, due to their electrical conductivity, Silicon Nitride-Titanium Nitride ceramic composite can be machined using an Electro Discharge Machine, which can produce surfaces that are resistant to both corrosion and biological degradation[2]. Si_3N_4-TiN ceramic composites are commonly used in fabrication of power generation components, modern gas burners, diesel engine glow plugs, bio medical implants, gas turbine for aerospace applications due to its maximum strength, maximum hardness, high creep resistance, and low temperature malleability[3]. The best level of tolerances and precision are required from the machined material, and this is accomplished by using the EDM process. Dimensional tolerances play an important role in fabrication of dies, gears, tools, molds, and press work operations fabricated through EDM developed process,[4] while machining the material, geometrical deviations needed to be carefully taken into account. As all industries would like to produce parts with exact, pre-determined dimensional accuracy at low costs.[5]. The width of cut (Kerf) significantly influences the dimensional accuracy of the final product, which is measured in micro meter. The width of cut is the estimated difference between the cutting width to the wire diameter. The material composition of the wire plays a crucial role in this regard[6].

According to Perumal K S et al. the electrode material has a significant impact on both machining performance and surface quality[7]. When machining Titanium alloys, Jie shing et al.[8] discovered that the electrode material significantly affects the rate of material removal, surface roughness, and electrode wear.

The electrode wear rates and machining efficiency of various EDM electrode materials were investigated by Nagrale et al.[9] in two different dielectric environments. The results of these investigations show the importance of considering electrode material choice when trying to achieve the desired machining outputs by electrical discharge machining (EDM).

Srinivasan and Palani.[10] experimented with peak current, pulse on time, pulse off time, spark gap voltage and wire feed rate, using a copper wire material on ceramic composite of Si_3N_4-TiN for surface roughness, wear rate and micro hardness. The results of the investigation show that, MRR was found to be influenced by higher peak current and longer pulse on duration. The parameters like voltage, current, and pulse on time have a significant effect on MRR and TWR, where current is the most significant one, other parameters are insignificant.

Selvarajan et al.[11] used multi parametric optimization on performance parameters like pulse on time, pulse off time and current using Taguchi and GRA for copper electrode and found that current was the most prominent parameter. They concluded that MRR increases and EWR decreases due to the influence of parameters like pulse on duration and current. The rate of material removal and surface roughness with graphite electrode are higher when compared with copper electrode were the findings of Selvarajan et al.[12], who further concluded that, the material removal rate (MRR) is higher for copper in relation to on time duration, whereas the graphite electrode gives higher MRR with current. Where pulse on time duration, current, and voltage are significant parameters.

Selvarajan et al.[13] used RSM to optimize the performance parameters for machining of Si_3N_4-TiN using square shaped copper electrode and found that current was the most prominent parameter. They concluded that MRR increases and EWR decreases due to the influence of parameters like pulse on duration and current.

Sunder J B et al.[14] used Taguchi's L_{27} Orthogonal array, for wire EDM of hybrid composite. The findings were analyzed using GRA for maximizing MRR and to minimized Kerf and surface roughness. The findings showed that, pulse off time, pulse on time and gap voltage were the most important parameters that influences the MRR. From the literature it is inferred that RSM is significant for optimizing the process parameters.

Taguchi based L9 orthogonal array was used for optimizing the process parameters by Raju K et al.[15] for Aluminum based metal matrix composite. Grey relational grade and GA were analyzed for maximizing MRR. It was concluded that current and on time duration and important parameters in the study. The results obtained for WEDM of Inconel 718 showed that using a zinc-coated brass wire electrode significantly improved the MRR and reduced the Kerf width significantly.[16]

Zinc-coated brass wire electrodes have been shown to provide better electrical conductivity, corrosion resistance, and reduced wire breakage during WEDM operations when compared to plain brass electrode materials. They are highly preferred in industries due to its performance and costing.[17] Several significant gaps persist, notably obtaining a more uniform, steeper width of cut, along with maximum cutting rates is a major challenge for researchers This needed to be addressed for the sake of dimensional accuracy, and sustainability of the product during manufacturing. Minimizing width of cut (Kerf) and maximizing cutting rates is a potential challenge before researchers for machining of ceramic composite, specially Si_3N_4-TiN composite.

Based on the literature review, it can be inferred that no research work has been conducted regarding the impact of a zinc-coated brass wire electrode on Si_3N_4-TiN ceramic composite in terms of cutting rates and Kerf width during wire-EDM operations. This paper investigates the effects of crucial parameters on cutting rates, such as current, pulse on time duration and short pulse duration, and develops optimal settings to enhance productivity in terms of cutting rates and establish regression model to predict cutting rates and width of cut by using response surface method. Further, objective of the work is to determine the optimum combination of EDM parameters on the performance characteristics.

2 Methodology

Si_3N_4–TiN composite, 35 % volume of TiN, suspended in the matrix was used as work material. The experiments were conducted by using Robofil 300, a wire electrical discharge machine (WEDM) manufactured by Charmilles Technology. Five-axis CNC WEDM machine. Zinc Coated brass wire (CuZn50) of 0.25 mm diameter was used as electrode. The deionized water was used as dielectric, and electrical conductivity was maintained at 15 μS/cm. The dielectric temperature was kept at 22°C Cutting rates were taken from the machine display, as well as average values in terms of mm^2/min. The cut-off length was selected as 10 mm. The work piece was 10 mm in thickness.

The Kerf widths were measured by using Nikon microscope with an optical magnification of ×100. The details of experimental condition are shown in Table 1.

Table 1. Details of the Experiment (Fixed Factors)

Machining parameters	Fixed levels
Work piece height	10 mm
Length of cut	10 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
Servo Reference Voltage (Aj)	60 V
Open circuit voltage (V)	-80 V
Strategy (ST)	1
Dielectric	Deionized water, 15μS/cm
Dielectric Temperature	22 C

*Rauschert GmbH ceramic composite

2.1 Design of experiments

RSM is a collection of statistical and mathematical procedures for the empirical modelling. This approach is used to ascertain the relationship between various input machining factors and their outputs. Wire EDM of Silicon Nitride -Titanium Nitride ceramic composite was developed based on central composite design method. Based on preliminary investigation, literature review and experience of machine operators, input parameters for twenty factorial trials were conducted[18].

The parameters that were selected for the input were pulse on-time (μs), short pulse duration (μs), and current (Ip). The experimental parameters' range and levels are displayed in Table 2.

Table 2. 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
Peak Current	Ip	Amps	160	240	320	400	480

2.1.1 Experimental Design

Analysis was carried out on cutting rate and width of cut (Kerf) as indicated by CR and Kerf respectively, as illustrated in **Table 3**. The results of the CCD experimentation were used to calculate the constants and coefficients of the models.

Table 3. Experimental Results of Cutting rates and Kerf

	Pulse on Duration	Short Pulse Duration	Peak Current	Cutting Rate	Width of Cut
	(μs)	(μs)	(amps)	mm^2/min	mm
Run	**T_{on}**	**T_{ac}**	**I_p**	**CR**	**Kerf**
1	0.8	0.4	320	49.72	0.37
2	1.2	0.6	480	59.23	0.38
3	0.4	0.2	480	44.43	0.36
4	1.2	0.2	480	51.04	0.37
5	0.4	0.6	480	35.85	0.35
6	1.2	0.4	320	69.72	0.36
7	1.2	0.2	160	57.67	0.35
8	0.8	0.4	320	54.33	0.36
9	0.8	0.4	320	54.33	0.36
10	0.8	0.4	320	61.41	0.35
11	1.2	0.6	160	55.24	0.35
12	0.4	0.2	160	62.32	0.36
13	0.8	0.1	320	41.11	0.36
14	0.8	0.4	320	54.33	0.36
15	0.8	0.4	320	54.33	0.36
16	0.8	0.4	320	54.33	0.36
17	0.8	0.7	320	31.85	0.36
18	0.4	0.6	160	43.12	0.34
19	1.0	0.4	320	53.97	0.35
20	0.8	0.4	320	54.33	0.36

3 Results and Discussion

Equations (1) and (2) represents the regression equations, developed using experimental data for Cutting rate and Kerf, to determine the real factors influencing the output parameters.

Regression Equation in Uncoded Units for Cutting rate:

$$CR = 86.28 - 50.39T_{on} \; + 44.22\, T_{ac} \;\; 0.11364\, I_p \; + 17.05\; T_{on} * T_{on} - 163.86\; T_{ac} * T_{ac} \\ + 0.000032\; I_p * I_p \; + 51.55\; T_{on} * T_{on} + 0.03998\; T_{on} * I_p \; + 0.09555\; T_{ac} * I_p \tag{1}$$

Equation (2) presents the regression equation that was developed using experimental data to determine the real factors influencing the Kerf width as a function of input parameters.

Regression Equation in Uncoded Units for Width of cut:

$$Kerf = 0.38468 - 0.02037\; T_{on} - \; 0.06701\; T_{ac} - \; 0.000038\;\; I_p - \; 0.01666\; T_{on} * T_{on} - 0.05093\;\; T_{ac} * T_{ac} \\ + 0.000000\; I_p * \; I_p + 0.08681\; T_{on} * \; T_{ac} + 0.000063\; T_{ac} * \; I_p + 0.000068\; T_{ac} * \; I_p \tag{2}$$

The determination coefficient (R^2) for Cutting Rate and Width of cut models are 0.99 and 0.97 respectively. It indicates very good fit and agreement between experiments and the model predictions.

3.1 Analysis of variance (ANOVA)

A variance analysis for cutting rate and kerf were made with the objective of analyzing the effects of pulse on duration, short pulse duration and current on the results.

The ANOVA results for the Cutting Rate and width of cut (Kerf) are delineated in the Tables 4 and 5 respectively. This variance analysis was carried out for 95% confidence level i.e., 5% significant level.

The final equations consist of all significant parameters including the coefficients. The adequacy of the proposed models was also checked by the variance analysis (F-test). The R value for the cutting rate and Kerf width models are 0.99 and 0.97

respectively.

It indicates very good fit and agreement between experiments and the model predictions. Further, the lack-of-fit is insignificant in cutting rate and Kerf width models. Tables 4 and 5 show the analysis of variance of the presented response surface regression equations. Figure 2**(a)** and **(b)** shows interaction plots of cutting rate and Kerf width respectively.

3.2 Cutting Rate

R-sq depicts that the model explains 99.35% variation in the responses. Further R-sq (adj) depicts 98.77% variation in responses of the model by significant terms. A p-value less than 0.05 indicates that the model terms are acceptable and are significant.

For linear terms current is found to be most significant followed by T_{on} and T_{ac}. The square terms of current are found to be more significant; rest are insignificant terms in the model. The 2-way interactions are significant for the model for T_{on} and I_p, the main effect plot is shown in Figure 2 **(c)**. Further the models lack of fit is greater than 0.05, which shows that the lack of fit is found to be insignificant, it depicts goodness of fit, that the proposed model fitted the experimental data.

3.3 Kerf Width

According to R-sq, the model accounts for 97.35% of variation in responses. The contribution of 95.60 % of significant terms in variation is depicted by R-sq (adj) for Kerf. A p-value of less than 0.05 for Kerf indicates that the model is significant. On time duration is the most important term followed by current and short pulse duration in linear terms. The two-way interactions are significant for short pulse duration and current. The model's lack of fit is determined to be negligible, similar to that of cutting rate, which indicates that the model is well fitted into the experimental data. Figure 2 **(d)** highlights the mean effect plot for width of cut.

Therefore, the proposed models for cutting rate and Kerf based on high R-sq values and insignificance of lack of fit will predict the responses accurately. Therefore, based on these parameters the proposed model is found to be fit for predictions.

Table 4. Analysis of variance for Cutting rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	1667.16	185.240	355.01	0.000
Linear	3	579.03	193.011	369.91	0.000
T_{on}	1	214.56	214.564	411.21	0.000
T_{ac}	1	139.91	139.914	268.15	0.000
I_p	1	224.55	224.554	430.36	0.000
Square	3	808.51	269.505	516.51	0.000
T_{on}*T_{on}	1	107.27	107.268	205.58	0.000
T_{ac}*T_{ac}	1	619.09	619.093	1186.50	0.000
I_p*I_p	1	12.01	12.006	23.01	0.001
2-Way Interaction	3	279.61	93.203	178.63	0.000
T_{on}*T_{ac}	1	136.04	136.043	260.73	0.000
T_{on}*I_p	1	59.13	59.133	113.33	0.000
T_{ac}*I_p	1	84.44	84.435	161.82	0.000
Error	10	5.22	0.522		
Lack-of-Fit	5	1.16	0.231	0.28	0.903
Pure Error	5	4.06	0.812		
Total	19	1672.37			

3.4 Discussion

3.4.1 Effect of input machining parameters on their response factors

- **Effect on cutting rate**

The most important parameter among all the machining parameters was determined to be pulse on-time, as illustrated in Figure 1**(a)** and **(c)**. A higher cutting rate is achieved by longer pulse. It is well known fact that on time pulse duration, current

Table 5. Analysis of variance for width of cut

Source	DF	AdjSS	AdjMS	F-Value	P-Value
Model	9	0.001666	0.000185	100.83	0.000
Linear	3	0.000938	0.000313	170.36	0.000
T_{on}	1	0.000115	0.000115	62.78	0.000
T_{ac}	1	0.000160	0.000160	87.15	0.000
I_p	1	0.000663	0.000663	361.14	0.000
Square	3	0.000152	0.000051	27.52	0.000
T_{on}*T_{on}	1	0.000102	0.000102	55.75	0.000
T_{ac}*T_{ac}	1	0.000060	0.000060	32.57	0.000
I_p*I_p	1	0.000000	0.000000	0.03	0.865
2-Way Interaction	3	0.000576	0.000192	104.62	0.000
T_{on}*T_{ac}	1	0.000386	0.000386	210.17	0.000
T_{on}*I_p	1	0.000147	0.000147	80.16	0.000
T_{ac}*I_p	1	0.000043	0.000043	25.53	0.001
Error	10	0.000018	0.000002		
Lack-of-Fit	5	0.000008	0.000002	0.81	0.589
Pure Error	5	0.000010	0.000002		
Total	19	0.001684			

and gap voltage increase due to increase in energy in the spark gap. This energy rises with increase in on time duration. This leads to increase in pulse frequency, thus leading to increase in cutting speed. The increase in cutting rate is attributed to increase in on time duration. This is because energy input is directly proportional to on time duration.

In these experiments, the peak current was varied along with pulse on time duration, and short pulse duration, keeping off time constant. The value of peak current rises with increase in on time duration. This is due to triangular wave form of current, which rises along the slope. From the machine setting, the current rise slope was set at 400 (A/ μs), therefore the peak current is at 400A at 1 μs of pulse on duration. The cutting rate is observed to increase with increase in peak current. The cutting rate rapidly increases when the peak current was from 320 A to 480A. However, the increased in cutting rate slows at higher range of peak current, as observed from Figure 1**(a)** and **(c)**.

This is explained by the fact that the materials contain ceramic particles in addition to TiN, which functions as a conducting material inside the matrix. The work piece's electrical and thermal conductivity decreases as a result of these ceramic particles in the matrix. Because they have a tendency to prevent the molten material from eroding, cutting rates are reduced at higher levels of current.

Since during machining of Si_3N_4-TiN composite, the electric sparks are formed at the conductive phase of composite, the discharged energy produces a very high temperature at the point of spark, leading to increase in cutting rates. Figure 2**(e)** illustrates the main surface plot for cutting rate, it is also apparent that the current is most significant among other factors which improves the cutting rate. Also, pulse-on duration is found to be the most dominating with respect to current for increasing the cutting rate. The effect of short pulse on time is moderately seen on the cutting rate as compared with respect to current and on time duration.

3.4.2 Effect on width of cut

The machined part's dimensional accuracy is determined by its Kerf width. The diameter of the wire in the gap, the spark gap, and the rate of material removal- all affect the Kerf width. [19] Width of cut or commonly referred as Kerf is crucial as it directly affects the accuracy and precision of the machined part. Smaller Kerf is desired for higher precision. The lower the Kerf width the better is the dimensional accuracy of the machining process whereas larger width of cut may compromise the dimensional accuracy. Although it may provide higher removal rates.

The creation of a network of electrically conductive TiN phases within the Si_3N_4 matrix is the mechanism underlying the electrical conductivity of SSi_3N_4-TiN composite. The primary factor affecting the electro-conductivity during machining is the distribution of TiN particles. Extended pulse duration raise peak current and, as a result, gap energy increase as observed from Figure 2 **(f)**. Because there is more energy in the gap, there is consequently more material removal at large on time. Greater applied energy in the gap and a higher rate of material removal (concentration of debris) cause the gap to widen. Figure 1 **(b)** and

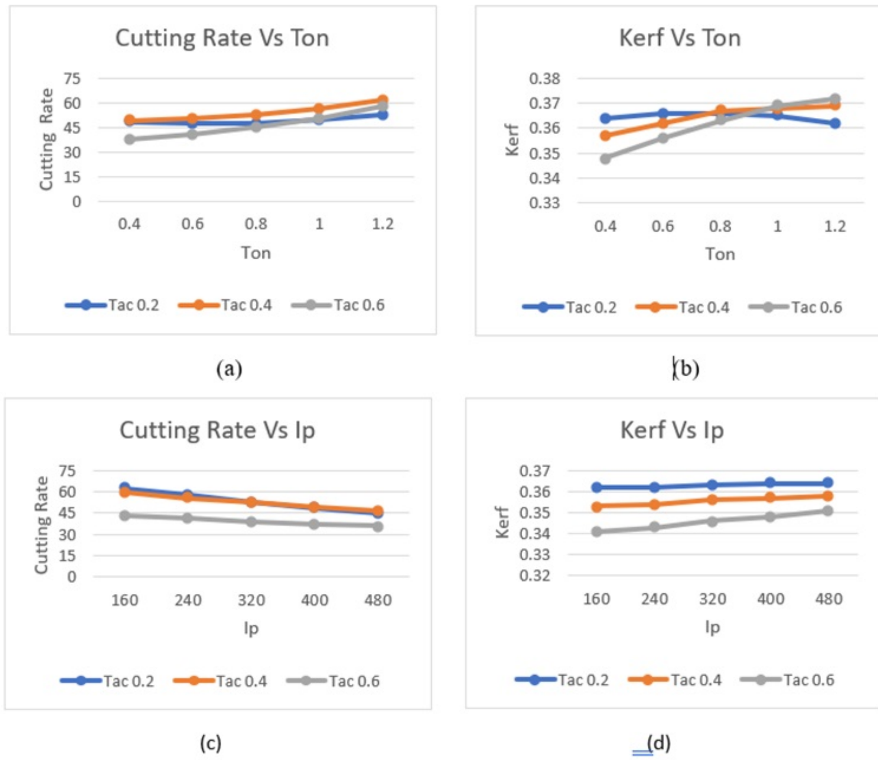

Fig 1. Effect of various process parameters and their responses. (a) Effect of Pulse on duration on Cutting rate, (b) Effect of Pulse on duration on width of cut, (c) Effect of current on Cutting Rate, (d) Effect of Current on Kerf

(d), highlights the effect of pulse on duration and current on width of cut. It was noticed that a wider Kerf width was caused by an increase in on-time. The narrowest width of the cut was also obtained during the experimentation with Si_3N_4-TiN ceramic composite, this was duly attributed to lower thermal and electrical conductivity of Si_3N_4 particles is higher as compared with that of TiN particles, leading to the requirement for much more thermal energy per unit volume to melt composite material, therefore the width of cut is narrower as observed, almost uniform throughout at various setting of performance parameters.

When compared to using a plain brass wire electrode for Si_3N_4-TiN composite, an increase in cutting rates of 4.39% is observed at minimum values of pulse duration and current, while an increment of 16.67% is noted when the pulse duration and current were at maximum values [20]. The emphasis of the current work is on achieving a notable cutting rate, as demonstrated by the experimental data, suggesting that zinc-coated brass electrode is a viable substitute for the molybdenum electrode used by Selvarajan et al. [17].

Consistent with the findings of this investigation, Luckas et al. concluded in his experimental work on Inconel 718 [16], that zinc-coated brass electrode offers better cutting rates than conventional bare brass electrode. Consistent with the results of the present investigation, Muttammara et al. [21] and Selvarajan et al. [13] have deduced from their research that the primary factor influencing cutting rates is current, which is attributed to its effect on width of cut.

Similar to this study, Murugan et al. [22] came to the conclusion that higher cutting rates are attained at elevated current intensity and pulse on duration, and that cutting rates are more sensitive to current intensity than to pulse on duration. The width of cut at high, average, and low values of pulse on time and current show a 28% difference. When using a copper electrode for SiC, which is roughly almost constant at variable values of the input parameters when compared with Nadeem et al. [19]

3.4.3 Optimization and cutting conditions

The optimal machining conditions for EDM of silicon nitride-titanium nitride ceramic composites using coated brass electrode are taken into consideration in order to maximize cutting rates and minimize the width of cut (Kerf). The goals and input parameter range for parametric optimization are shown in Table 6.

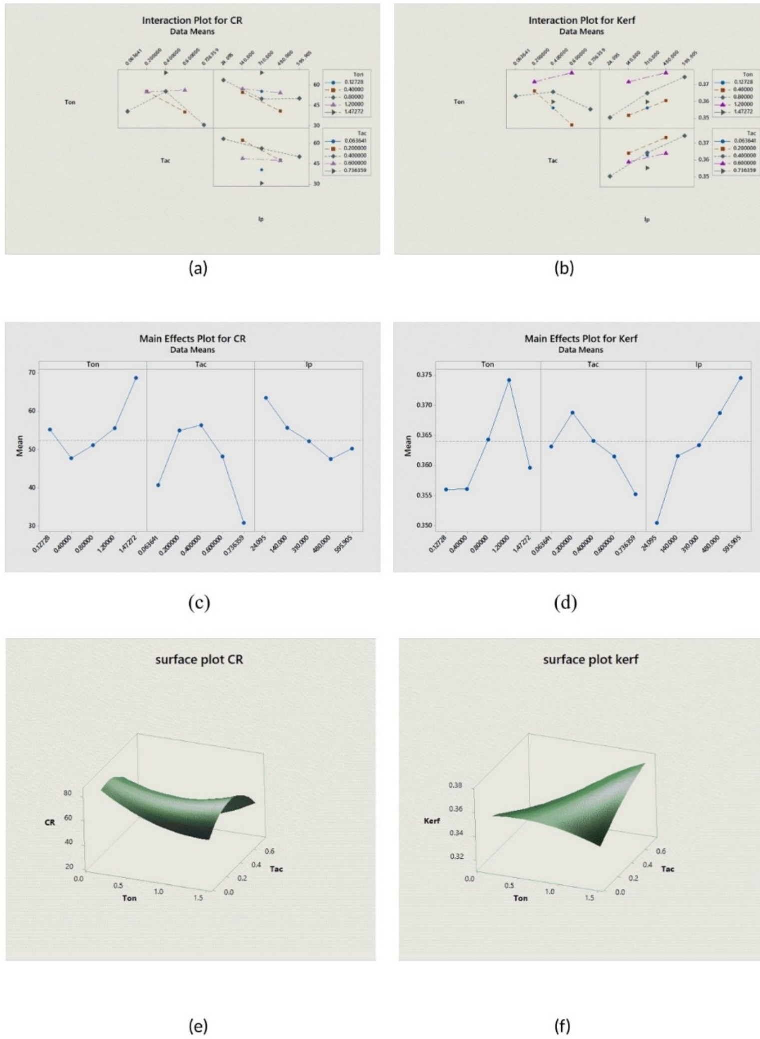

Fig 2. Various interaction plots. (a) interaction plot for cutting rates, (b) interaction plot for Kerf, (c) Main effect plot for CR, (d) Main effect plot for Kerf, (e) Surface plot for CR, (f) Surface plot for Kerf

Table 6. Goals and factors for optimization of machining conditions

Condition	Symbols	Goal	Lower Limit	Higher Limit
Pulse on duration	T_{on}	In the range	0.40	1.20
Short pulse duration	T_{ac}	In the range	0.20	0.6
Peak Current	I_p	Maximize	240	480
Cutting Rate	CR	Maximize	30.80	65.77
Width of cut	Kerf	Minimize	0.34	0.35

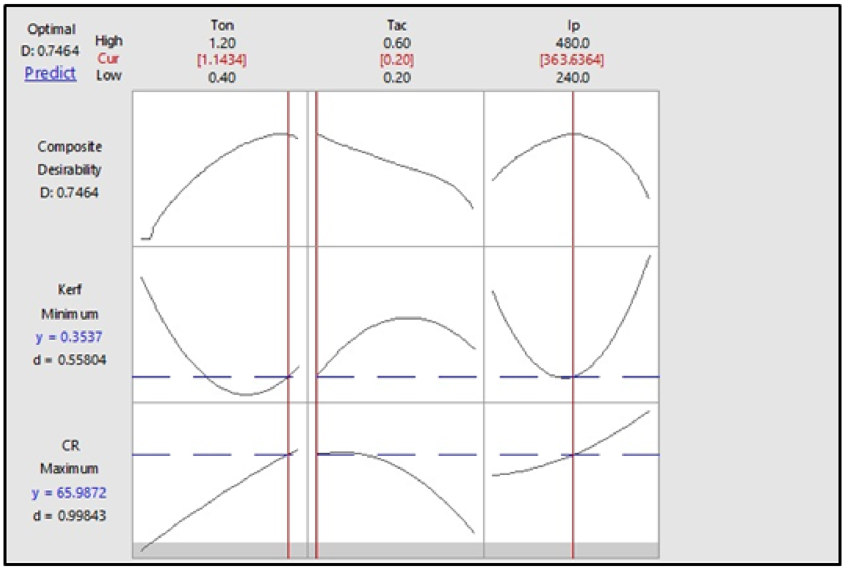

Fig 3. Optimization plot

The optimization plot is shown in Figure 3. As inferred from Figure 3, the maximum cutting rate of 65.98 mm^2/min is obtained at an on-time duration of 1.14 μs, 0.2 μs for T_{ac} and 363.63 A for current at Kerf of 0.3537mm. Considering the limitation of the experimental set up, confirmatory tests were carried out at on- time duration of 1.2 μs, T_{ac} of 0.3 μs, and current of 320 A, which resulted in 69.72 mm^2/min of cutting rate and yielded 0.35mm Kerf. With an average error of around 5 % for cutting rate and 1.05 % for width of cut, the developed models can be used to predict cutting rates and width of cut accurately.

4 Conclusion

The Si_3N_4–TiN ceramic composites materials are categorized under difficult-to machine material and it is machined by EDM process using coated Brass electrode.

The following are the conclusion:

- Improved cutting rates and reduced Kerf width are provided by zinc-coated brass wire electrode.
- The optimal conditions for maximum cutting rates and minimum Kerf are 69.72 mm^2/min, Kerf at 0.35 mm at T_{on} of 1.2 μs, T_{ac} of 0.3 μs, and current of 320 A. These parameters were obtained from the RSM.
- The suggested correlations between cutting rate and Kerf width had R values of 0.99 and 0.97, respectively.
- An average error of 5% for cutting rate and 1.05% for width of cut was noted between actual and predicted values, highlighting that the model can be used to predict the responses accurately.
- The use of a moderately short pulse duration of 0.4 μs and an average current of 320 A can yield the highest cutting rates when using a high value of 1.2 μs for the pulse duration.
- For a pulse on duration of 0.4 μs and a minimum current of 160 A, the lowest values of width of cut can be obtained. The ideal machining parameters were determined from the RSM.
- Coated brass wire is a good candidate for machining of Si_3N_4-TiN ceramic composite.
- The performance measures of the surfaces, including surface integrity, surface quality, and surface alteration, will be the subject of future research.

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