Silicon (2022) 14:547–555
https://doi.org/10.1007/s12633-020-00848-w

ORIGINAL PAPER

Investigations on Electric Discharge Machining Behaviour of Si_3N_4 -TiN Ceramic Composite

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Received: 21 September 2020 / Accepted: 17 November 2020 / Published online: 24 November 2020

Abstract
Ceramic composites are deliberated as an important material for their increasing advantages in aircraft, automotive and nuclear industries. But, these composites are very difficult to cut by conventional machining. Hence, the unconventional machining process like electric discharge machining (EDM) is reflected to be an essential machine for its capability to machine at any type of materials irrespective of its natural behaviour. In the present work is, to investigate the effects of EDM parameters on Si_3N_4-TiN ceramic composite by using taper shape of copper electrode. An L9 orthogonal array experimental plan is utilized to machining the composite by considering three input factors like pulse current, pulse on-time and pulse off-time. The material removal rate (MRR), over cut (OC) and taper ratio (TR) are considered as the machining performance characteristics. Taguchi combined with grey relational analysis (GRA) are employed to determine the best combination of EDM factors on multiple responses. An experimental result shows that, the optimal combination of parameters found to be pulse current at level 2 (1.0 amps), pulse on-time at level 1 (3 μs) and pulse off-time at level 2 (4 μs). ANOVA results noticed that pulse current is atmost impact parameter with influence of 65.47% subsequently by pulse on-time with contribution of 21.12% respectively. Finally, the confirmation test was conducted to validate the experimental results by using the optimized parameters.

Keywords Si_3N_4-TiN · EDM · Taguchi method · Grey relational analysis · ANOVA

1 Introduction

In recent decades, the need for products containing complicated features has revealed a prominent and balanced development. In fact, very small size of holes are employed for numerous resolutions in a number of products, such as diesel fuel injection nozzles, cooling channel in turbine blades, spinner holes, drug delivery orifices and inkjet printer nozzles [1]. EDM is a well-known precision machining process which can make the small holes in the hard materials as it is a non-contact material removal process [2]. The main demerits of this method is it gives low MRR, poor surface finish and poor geometry quality. In the past research, various techniques were adopted to rectify these drawbacks by using dielectric fluid mixed with powder, rotation methodology, vibration aided machining, debris flushing techniques etc. [3]. In EDM, the electrode gap is too small for internal flushing. As there is very small gap between work piece and tool electrode, it causes the control processes into too complex and a bridge is developed between the work surface and the tool surface due to debris accumulated which permitting arcing and radial surface sparking to occur and this leads to unsatisfactory performances such as low MRR, over sized hole, tapered hole and poor surface finish. Thanigaivelavan et al. [4] reported that the conical with rounded electrode provide the higher MRR with lesser over cut. Sohani et al. [5] it was undoubtedly apparent that the best shape of tool for greater MRR and minimum TWR is circular, followed by triangular, rectangular and square shape of tool electrode. Aliakbari et al. [6] proposed that increase of hole numbers in the tool electrode causes better flushing conditions thereby increases the MRR and EWR. Shuliang Dong et al. [7] have developed a new method

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using multi-diameter electrode with different dielectric fluids in the micro EDM process for improving micro hole quality of Be-Cu alloys. They reported that quality of surface was enhanced by using multi-diameter electrode and two different dielectric fluids like deionized water and kerosene. Kan Wang et al. [8] compared the cylindrical and helical shape tool and concluded that helical tool is a better tool than cylindrical shape electrode in the micromachining for improving the MRR. Kao et al. [9] has applied the Taguchi based GRA to improve the multi performance responses in the EDM process on Ti–6Al–4 V alloy. Reza Teimouri et al. [10] investigated the response of EWR and OC were increased when applying the magnetic field around the machining gap. Jahan et al. [11] concluded that the low frequency vibration at the low discharge energy condition enhances the surface quality and dimensional accuracy of tungsten carbide in the micro EDM. Huang et al. [12] observed that the WC tool electrode with coating of TiN gives the reduced overcut and the lowest EWR during the micro EDM process. Yusufzai at el. [13] investigated the influence of tool shape and size factor on output responses and they observed that cylindrical tool has obtain the better surface finishing with greater MRR than square tool in the EDM of aluminium matrix composites. Narcis Pellicer et al. [14] observed that the **s**quare and rectangle geometry electrodes reveal better radial and axial wear ratios than other tool shapes in the EDM. Mustafa et al. [15] investigated the effect of EDM variables like pulse current and pulse duration on machining characteristics of Inconel 718 super alloy. They understood that hole taper, hole dilation and electrode wear improves when rising both discharge

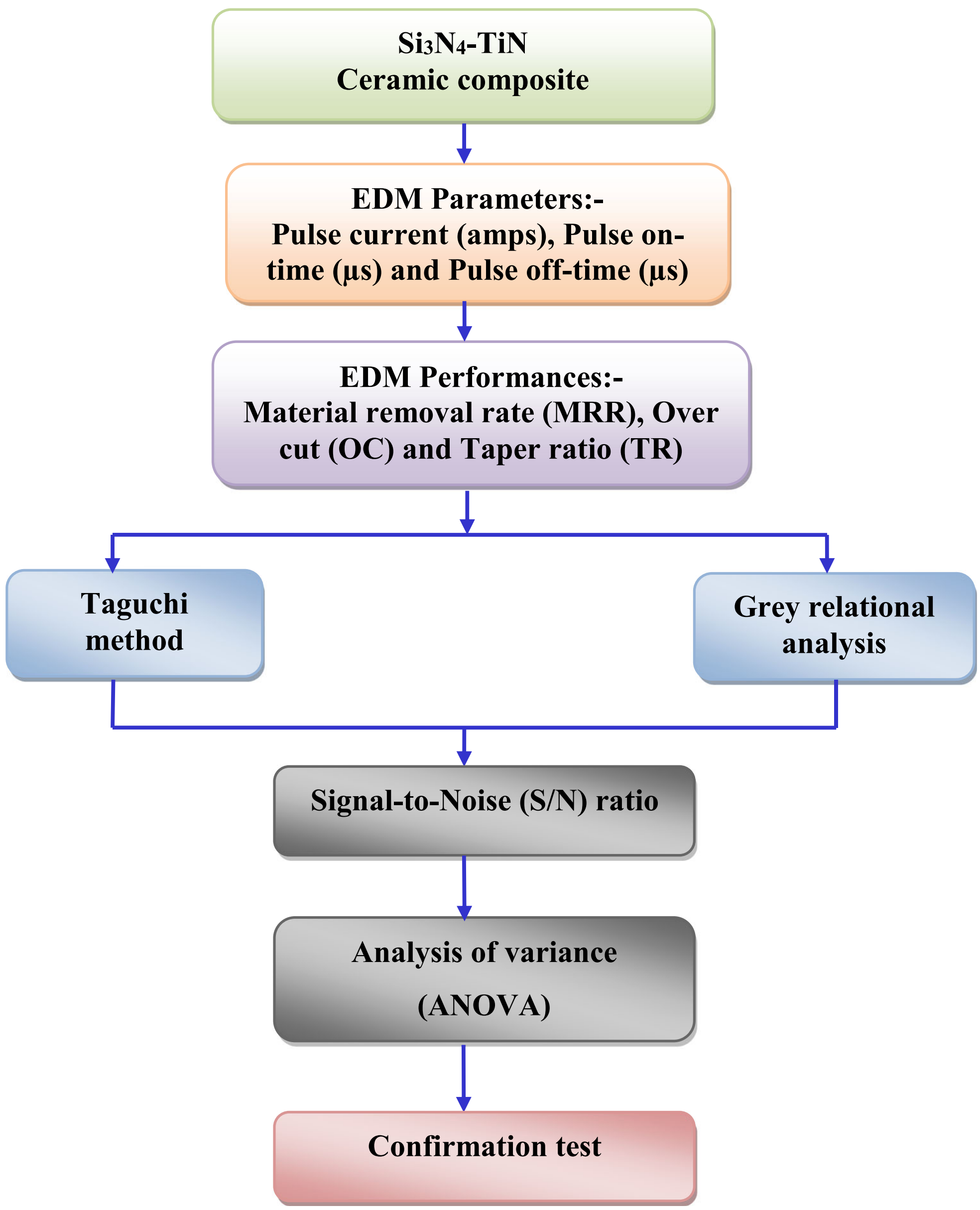

Fig. 1 Methodology of present work

current. Also it was seen that the crack and surface damages of machined micro hole has been reduced by decreasing the current and pulse duration. Mathan kumar et al. [16] analyzed the effects of various tool geometry on EDM performances and observed that result showed the circular tool electrode as the best tool shape configuration with minimum TWR and greater MRR during machining of Al/10wt%SiC_p MMC. Selvarajan et al. [17] used new machining parameters of EDM on Si_3N_4-TiN ceramic composite and the performance like circularity, cylindricity and perpendicularity were analyzed by applying GRA of the Taguchi method.

An attempt has been made to study the impact of taper shape tool electrode on EDM process of Si_3N_4-TiN ceramic composite. The objective of the work is to determine the optimum combination of EDM parameters on the performance characteristics by using Taguchi combined GRA. Furthermore, ANOVA is employed to detect the significant order of input parameters and the percentage contribution of that parameter is also determined. Figure 1 displays the steps involved in the methodology of current research work.

2 Experimental Details

In this work, Si_3N_4-TiN ceramic composite was selected as a work material due to its outstanding properties like light weight, high hardness, high specific strength at high temperature, oxidation and thermal shock resistance [18]. It is used as a component in the manufacture of high speed ball bearings of gas turbines, nozzles, automotive engine components, turbine impeller, cutting tools and heat shield products [19]. The composite used in this research work was purchased from a Saint-Gobain ceramic supplier. The properties of received Si_3N_4-TiN ceramic composite are depicted in Table 1. The scanning electron microscope (SEM) image and energy dispersive x-ray (EDX) pattern of Si_3N_4-TiN composite is shown in Fig. 2. It was evident that the presence of Si and Ti peaks in the composites.

The composite was machined by die sinking method of EDM process. Figure 3(a) display the equipment employed for the conduct of experiments (Electronica Machine Tools,

Table 1 Properties of Si_3N_4-TiN composite

Properties	Si_3N_4-TiN composite
Density (g/cm^3)	4.01
Tensile strength (MPa)	350
Hardness (HRA)	90.5
Fracture toughness (MPa)	5.7
Young's modulus (GPa)	341
Specific heat (J/Kg-K)	630
Thermal conductivity (W/mk)	19.1
Electrical resistivity (Ω m)	7.24×10^{-6}

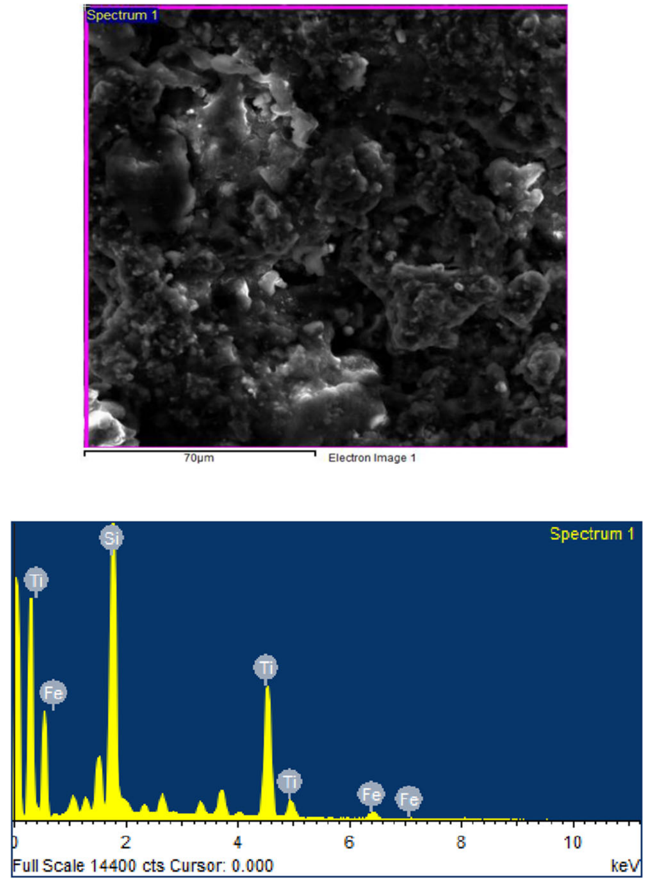

Fig. 2 SEM and EDX image of Si_3N_4-TiN composite

Kolkata, India). A cylindrical with taper shape of copper electrode having a diameter of 700 µm was used as a tool. SEM image of taper electrode is shown in Fig. 3(b). The uniform depth of drilled hole in the work piece was maintained at 2 mm kept for all the experiments. The machined Si_3N_4-TiN composite material is shown in Fig. 3(c). The weight of work piece before and after machining was taken by digital weighing machine (Make-Japan, accuracy of 0.001 g). Measurements of drilled holes were taken by using optical profile projector (OPTOMECH, Model-400TE, Hyderabad, India) with digital reader. The MRR, overcut (OC) and taper ratio (TR) were calculated by using formula used in the earlier literatures [7, 17]. The upper and bottom sides of the micro holes were scanned by scanning electron microscopy (SEM, ZEISS equipment, Make-Jena, Germany) in order to ascertain the overcut and taper ratio.

In this investigation, three EDM process parameters were identified as the most impact factors on the EDM performance characteristics of composites with an objective to maximize the MRR and minimize the OC and TR [20]. The input data with its levels are presented in Table 2. Furthermore to decrease the number of experiments needed to find the optimal level for the parameters chosen, a standard Taguchi L9 (3^3) orthogonal array was employed to execute the experiments as shown in Table 3.

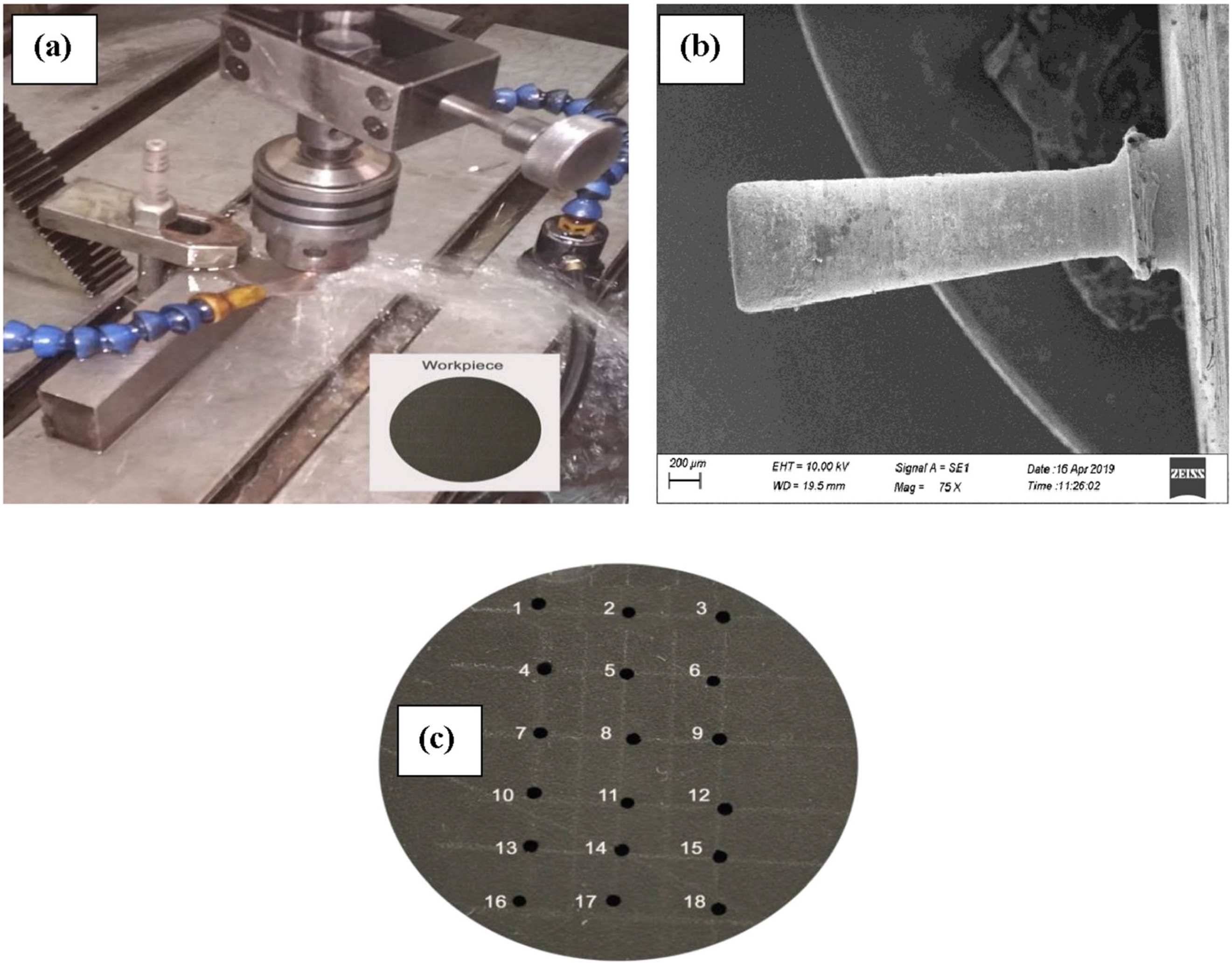

Fig. 3 (**a**) Experimental setup (**b**) SEM image of taper electrode and (**c**) machined Si_3N_4-TiN composite

3 Results and Discussion

3.1 Multi-Response Optimization Using Grey Relational Analysis

The GRA is effectually utilized to resolve the difficult problems with interrelationships between the multi objective characteristics [21]. In this investigation, GRA was employed to determine the optimum level of EDM parameters on the multiple objective of the responses. Grey relational analysis was carried out by the following steps:

Step 1: In this step, S/N ratio was calculated. In the EDM process, the maximum MRR and minimum OC and TR were selected the best performance characteristics. Hence, the MRR is selected as a larger - the - better S/N ratio and the OC and TR are considered as smaller-the-better S/N ratio it was evaluated by applying Eqs. (1) and (2). [22]

$$\text{S/N ratio} = -10\log_{10}(1/n)\sum_{k=1}^{n}\frac{1}{{Y_{ij}}^2} \quad (1)$$

$$\text{S/N ratio} = -10\log_{10}(1/n)\sum_{k=1}^{n}{Y_{ij}}^2 \quad (2)$$

Where n – number of replications, Y_{ij} – obtained responses where i = 1, 2, 3…..n; j = 1, 2, 3…….k.

Table 2 Machining parameters with its level

Symbol	Machining parameter	Units	Level		
			1	2	3
A	Pulse current	amps	0.5	1.0	1.5
B	Pulse on-time	µs	3	6	9
C	Pulse off-time	µs	2	4	6

Table 3 L9 orthogonal array of input parameters and output responses

Sl. No	Pulse current (amps)	Pulse on-time (µs)	Pulse off-time (µs)	MRR (g/min)	OC (mm)	TR
1	0.5	3	2	0.000380	0.05246	0.00687
2	0.5	6	4	0.000526	0.04906	0.00813
3	0.5	9	6	0.000394	0.05348	0.00690
4	1.0	3	4	0.000518	0.04795	0.00730
5	1.0	6	6	0.000539	0.05313	0.00769
6	1.0	9	2	0.000489	0.05973	0.00710
7	1.5	3	6	0.000517	0.06082	0.00732
8	1.5	6	2	0.000528	0.07440	0.00763
9	1.5	9	4	0.000554	0.07883	0.00782

Step 2: In this step, Normalization S/N ratio was calculated. Here, the obtained response values were normalized and rated between 0 and 1. For the performance value of "smaller-the-better characteristics" the original order is normalized as Eq. (3). [23]

$$Y_i^*(k) = \frac{\max Y_i(k) - Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad (3)$$

The performance value of "larger -the-better characteristics" the original order is normalized by utilizing Eq. (4).

$$Y_i^*(k) = \frac{Y_i(k) - \min Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad (4)$$

Where Y_i^* (k) - is the sequence after the pre-processing, Y_i (k) – is the original sequence of performance values, max Y_i (k) & min Y_i (k) – is the maximum and minimum value of Y_i (k) for the k^{th} -response. The S/N ratio values for the MRR, OC and TR are provided in Table 4.

Step 3: The grey relational coefficient ξ_i (k) for the output results were calculated from the normalized S/N ratio by using Eq. (5). [23]

$$\xi_i(k) = \frac{\Delta\min + \zeta \cdot \Delta\max}{\Delta_{0i}(k) + \zeta \cdot \Delta\max} \quad (5)$$

Where,

(i) k = 1, 2, 3,…., m; i = 1, 2, 3,…, n. m - is the number of responses and n - is the number of experimental values. For the present analysis, m = 3 and $n = 9$.
(ii) $\Delta_{0i}(k) = \|Y_0^*(k) - Y_i^*(k)\|$ -is the absolute value of the difference between Y_0^* (k) and Y_i^* (k).
(iii) $\Delta_{0i}(k)$- is the deviation sequence, Y_i^* (k) – is the comparability sequence, Y_0^* (k) - is the reference sequence whose value is equal to 1.
(iv) $\Delta\min = \min\min \|Y_0^*(k) - Y_i^*(k)\|$- is the minimum value of Y_i^* (k).
(v) $\Delta\max = \max\max \|Y_0^*(k) - Y_i^*(k)\|$ - is the maximum value of Y_i^* (k).
(vi) ζ- is the distinguishing co-efficient, value is taken as 0.5).

Step 4: The grey relational grade (GRG) was obtained by averaging the GRC for individual performance characteristics and the Eq. (6) was used. [23]

Table 4 Calculated S/N ratio and normalized S/N ratio

Sl. No	S/N Ratio (dB)			Normalized S/N Ratio (dB)		
	MRR	OC	TR	MRR	OC	TR
1	11.59567	−14.3966	−16.7391	0	0.854113	1
2	14.41971	−13.8146	−18.1965	0.839080	0.964216	0
3	11.90992	−14.5638	−16.777	0.080460	0.820920	0.976190
4	14.28660	−13.6158	−17.2665	0.793103	1	0.658730
5	14.63178	−14.5068	−17.7151	0.913793	0.832189	0.351587
6	13.78618	−15.5239	−17.0252	0.626437	0.618459	0.817460
7	14.26981	−15.6809	−17.2902	0.787356	0.583225	0.642857
8	14.45268	−17.4315	−17.6528	0.850575	0.143459	0.395238
9	14.87020	−17.9338	−17.8675	1	0	0.243651

Table 5 Grey relational co-efficient and grade with rank

Sl. No	Grey relational co-efficient			Grey relational grade	Rank
	MRR (ξ_1)	OC (ξ_2)	TR (ξ_3)		
1	0.333333	0.774129	1	0.702487	2
2	0.756522	0.933212	0.333333	0.674356	5
3	0.352227	0.736290	0.954545	0.681021	3
4	0.707317	1	0.59434	0.767219	1
5	0.852941	0.748715	0.435384	0.679013	4
6	0.572368	0.567188	0.732558	0.624038	6
7	0.701613	0.545390	0.583333	0.610112	7
8	0.769912	0.368584	0.452586	0.530361	9
9	1	0.333333	0.397979	0.577104	8

$$\gamma_i = \frac{1}{m} \sum_{k=1}^{m} \xi_i(k) \tag{6}$$

Where γ_i - is the GRG for the ith experiment, ξ_i- is the GRC and m – is the number of output responses. Table 5 depicted the calculated GRC and GRG with order in rank. From the Table 5, it was observed that the larger value of GRG indicates that the compatible mingling of parameter is near to the optimum level.

Figure 4 display the GRG versus experiment number and it was proved that the experiment number 4 has a higher GRG (0.767219), which consisting a recommended level of optimal EDM parameters (pulse current = 1.0amps, pulse on-time = 3 μs and pulse off-time = 4 μs) with an target of maximizing the MRR and minimizing the OC and TR for the EDM process of Si_3N_4-TiN ceramic composite.

3.2 Analysis of EDM Parameters

Figure 5 show the response plot of mean GRG for the concerned input machining parameters. From the plot, the dashed line represented the median value of mean GRG and the tallest value indicate an forecasted multiple purpose of characteristics.

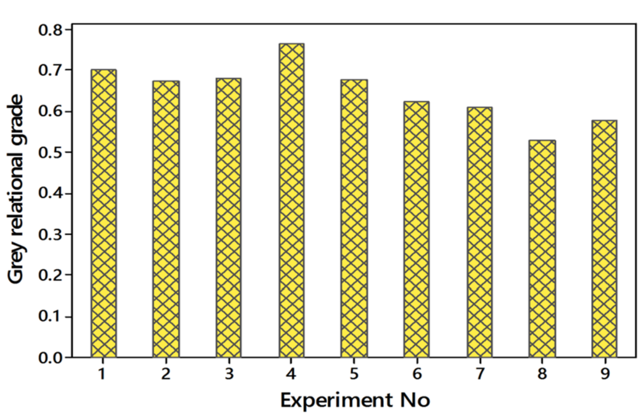

Fig. 4 Rank plot for GRG

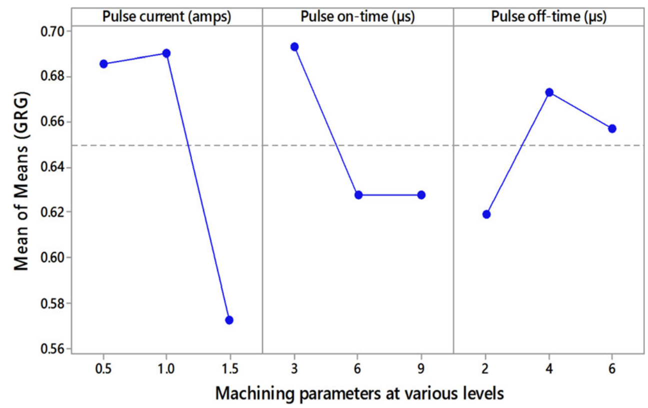

Fig. 5 Response plot for mean GRG

It was clearly found that the optimum level of parameters are $A_2B_1C_2$, which shows the pulse current level at 2 (1.0 amps), pulse on-time level at 1 (3 μs) and pulse off-time level at 2 (4 μs). This combination of input parameters make upgrade the multiple performance characteristics during EDM process of Si_3N_4-TiN ceramic composite. The mean grey relational grade for input level parameters and the average GRG are provided in Table 6. From the table, the significant effect of input factors was calculated by finding difference between the greatest and the smallest values of mean GRG and it is represented as delta (Δ). The higher value of the delta indicates that the eminent factor on the responses. From Table 6, it can be understood that the pulse current was extremly significant factor on multiple response characteristics of produced composites, subsequently pulse on-time. The result is similar to that obtained by Eckart Uhlmanna et al. [24].

3.3 Analysis of Variance (ANOVA)

ANOVA is a statistical tool to determine the significant effects of each parameter on the output performances under investigation [25]. The objective of the ANOVA is to pointout the dominated design parameters than the others and the contribution of that parameter [26]. In the current work, ANOVA was effectively applied to find out the contribution of EDM parameters on the multiple response characteristics like MRR, OC and TR. The result of ANOVA and percentage contribution of each parameter for mean GRG is depicted in Table 7

Table 6 Response table for mean GRG

Level	Pulse current (A)	Pulse on-time (B)	Pulse off-time (C)
1	0.6860	0.6933	0.6190
2	0.6901	0.6279	0.6729
3	0.5725	0.6274	0.6567
Delta	0.1176	0.0659	0.0539
Rank	1	2	3

Total mean GRG = 0.649523

Table 7 ANOVA results for GRG

Source	DF	Seq SS	Adj SS	Adj MS	F-ratio	*P* value
Pulse current (A)	2	0.0267046	0.0267046	0.01333523	30.72	0.032
Pulse on-time (B)	2	0.0086135	0.0086135	0.0043067	9.91	0.092
Pulse off-time (C)	2	0.0045956	0.0045956	0.0022978	5.29	0.159
Residual error	2	0.0008692	0.0008692	0.0004346		
Total	8	0.0407829				

S = 0.0208472; R-Sq = 97.87%; R-Sq(adj) = 91.47%

and Fig. 6. It was clearly revealed that pulse current was the most important parameter among the others that contribution of 65.47% on the multiple quality characteristics of Si_3N_4-TiN ceramic composite subsequently by pulse on-time has a contribution of 21.12% and pulse off-time has a less contribution of 10.99%. The residual error contribution is only 2.13%. The Fisher's (F-ratio) test was employed at 95% confidence interval (CI). The F-ratio of pulse current and pulse on-time were greater than $F_{(0.5,2,8)} = 4.46$, also it ensures the statistical physical impact on the combined multiple responses. Yan-Cherng Lin et al. have observed the similar findings during the EDM process of ZrO_2 and Al_2O_3 ceramic composite. They reported that peak current was the most important factor for improving the MRR. For reason is that, increase in current delivered the larger amount of discharge energy into the machining zone which makes dramatic temperature gradient for ceramic composites compared with other materials [27].

3.4 Interaction of Machining Parameters with GRG

Fig. 7(a-c) display the interaction plot for achieved grey relational grade with respect to machining parameters. This plot extensively used to analze the interaction of each parameter on the effect of multi performance characteristics of the machined composite. In Fig. 7(a), the interaction between the pulse on-time and pulse current clearly indicates that higher pulse current decreases the mean GRG at maximum level pulse on-time. The small level pulse on-time (3 µs) gives the higher mean GRG at all level of pulse current. The maximum GRG is

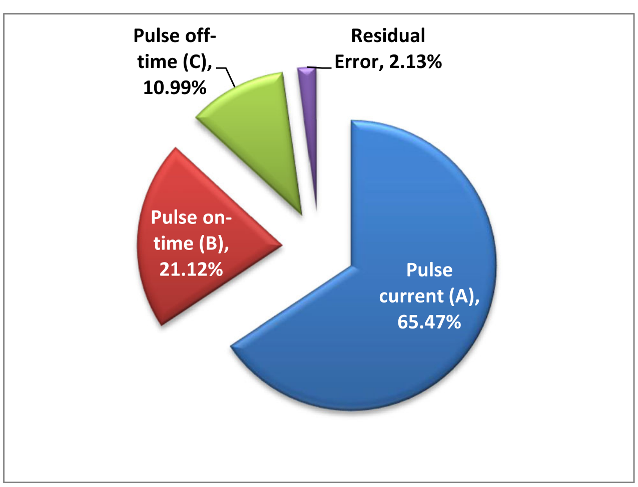

Fig. 6 Contribution of parameters on GRG

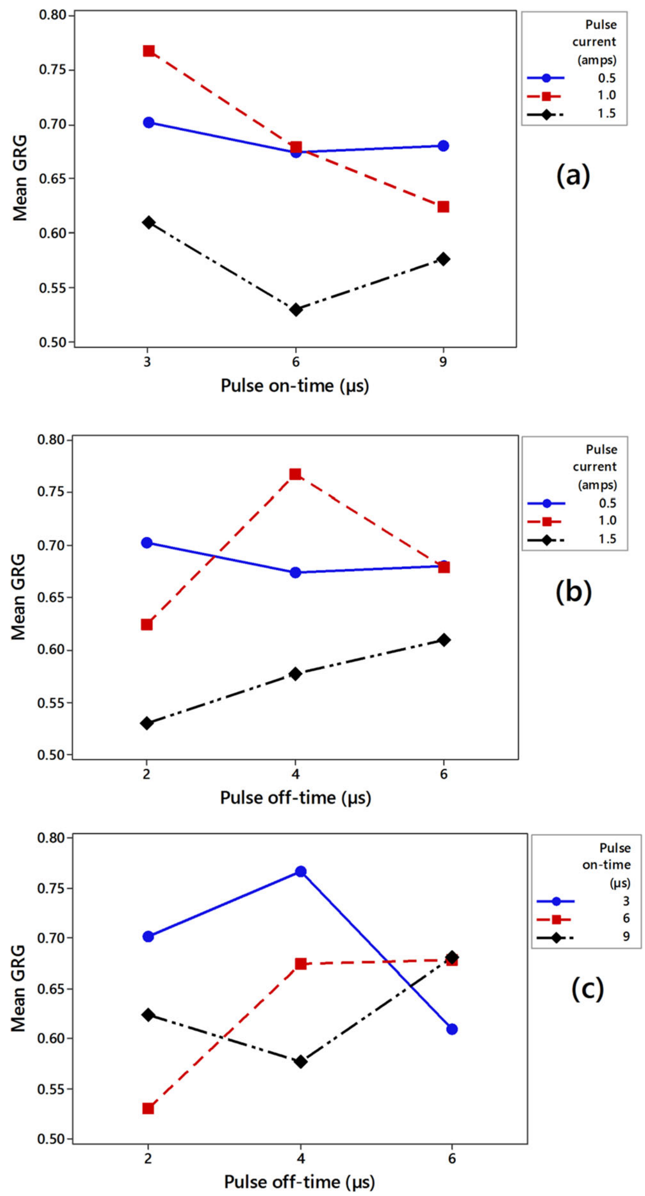

Fig. 7 Interaction plot for GRG (**a**) pulse current vs. pulse on-time, (**b**) pulse current vs. pulse off-time and (**c**) pulse on-time vs. pulse off-time

achieved at low value of pulse on-time (3 μs) and middle level of pulse current (1.0 amps). From the Fig. 7(b), the interaction between the pulse current and pulse off-time on mean GRG. It can be clearly observed that, the middle level of pulse current (1.0 amps) improved the mean GRG at middle level of pulse off-time (4 μs). The high setting of pulse current decreases the mean GRG at all levels of pulse off-time. The low level of pulse current slightly improved the mean GRG at low level of pulse off-time (2 μs). In Fig. 7(c) show that interaction of pulse on-time and pulse off-time on mean GRG. It is noticed that the low value of pulse on-time (3 μs) gives the higer GRG at middle level of pulse off-time (4 μs). The low setting of pulse off-time (2 μs) obtained minimum GRG at middle level of pulse on-time (6 μs). However, the higher mean GRG is attained by the middle level setting of pulse on-time (6 μs) and pulse off-time (4 μs).

3.5 Confirmation Test

The confirmation test was performed to valitate the optimal level of input parameters during EDM process of Si_3N_4-TiN ceramic composites. The predicted value of GRG is obtained by using Eq. (7). [28]

$$\gamma_{pre} = \gamma_m + \sum_{k=1}^{n} (\gamma_i - \gamma_m) \tag{7}$$

Where, γ_{pre}- predicted GRG, γ_m- total mean GRG, γ_i- is GRG mean at the optimal level and k- number of EDM parameters. Table 8 display the value of predicted and experimental GRG using optimal level parameters and these values are very close to each other. The GRG from the initial parameter setting to the optimum parameter setting improved to 0.064732. Hence, this methodology for optimal analysis parameters for multi performance characteristics is possible. Figure 8 displays the probability graph for GRG and it clearly indicates that all the errors are regularly fitted over the straight line at 95% CI.

Table 8 Results of confirmation test

Response parameters	Optimal machining parameter		
	Initial	Predicted	Experimental
Setting level	$A_1B_1C_1$	$A_2B_1C_2$	$A_2B_1C_2$
MRR (g/min)	0.000380	–	0.000518
OC (mm)	0.05246	–	0.04795
TR	0.00687	–	0.00730
GRG	0.702487	0.757254	0.767219

Improvement of GRG = 0.064732

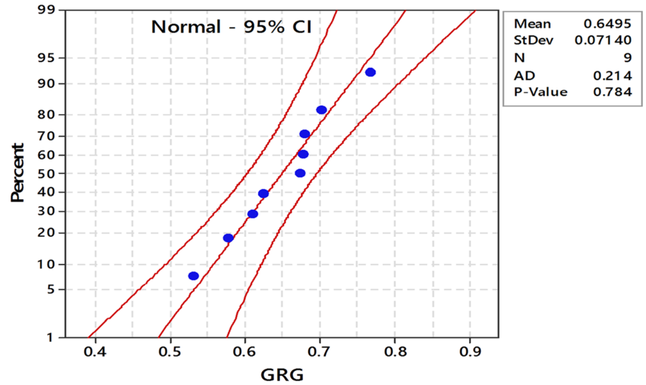

Fig. 8 Normal probability plot of GRG

4 Conclusions

In this work, EDM characteristics of Si_3N_4-TiN ceramic composite was studied and the detailed conclusions were drawn.

- The SEM analysis clearly shows the fine dispersal of Si_3N_4 and TiN particles in the developed composite.
- The effects of EDM parameters such as pulse current, pulse on-time and pulse off-time on the multiple response characteristics were determined by using GRA to maximize the MRR and minimize the OC and TR.
- The optimum combination of EDM parameters are $A_2B_1C_2$ (Pulse current is 1.0amps, Pulse on-time is 3 μs and Pulse on-time is 4 μs), which was identified through grey relational grade.
- From ANOVA analysis, it can be revealed that the pulse current ($P = 65.47\%$) was highly influenced on the multiple response characteristics followed by pulse on-time ($P = 21.12\%$).
- The confirmation test was performed by the optimum level of EDM parameters and the experimental results are very close to the predicted results.

Acknowledgements The authors are grateful to the CIPET (Central Institute of Plastics Engineering and Technology), Madurai, Tamilnadu, India for providing the testing facilities to this investigations.

Availability of Data and Material Not applicable.

Authors' Contributions All authors have done equal contribution.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Consent to Participate Yes. All equally participated.

Consent for Publication Yes granted.

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