Analysis and Optimization of EDM Parameters on Si_3N_4-TiN Composite using Multi-Diameter Electrode

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Abstract

This paper presented the multi-response optimization of machining parameters is performed in rotary electrical discharge machining (EDM) on Si_3N_4-TiN composite using grey based Taguchi method. The effects of combination method of EDM (Rotary EDM for I^{st} step minor diameter and Sinking EDM for 2^{nd} step major diameter of tool electrode) on responses have been analyzed. The machining method consists of two processing stages which are carried out in sequence, namely Rotary and Sinking EDM. Taguchi $L_9(3^3)$ orthogonal array was used to formulate the experimental layout and experiments were conducted on Si_3N_4-TiN composite with copper multi-diameter electrode. Three input variables such as pulse current, pulse-on time and method of EDM, while material removal rate (MRR), over cut (OC) and taper ratio (TR) were chosen as output responses. From main effect plot showed that the optimum level of parameters are pulse current at 1.0 amps, pulse-on time of 6 µs by using combination of rotary and sinking EDM method. ANOVA results revealed that the method of EDM and pulse current are the most dominant parameters with contribution of 53.95% and 21.38% respectively..

Keywords: *Si_3N_4-TiN, EDM, Multi-diameter electrode, MRR, OC, TR, Grey relational analysis and ANOVA.*

1. Introduction

Demands for the high tech engineering ceramics components are increasing, as it has very outstanding properties. Si_3N_4 is one of the best suitable ceramic materials for structural application among various ceramic materials like Al_2O_3, ZrO_2, B_4C, etc., because of it has low density, good hardness, oxidation and thermal shock resistance. In spite of its excellent properties, there are some difficulties on machining and fabrication of the material. Therefore, applications of the ceramic material in the industry are very limited. Many researchers have found the solution for set right these drawbacks by improving the electrical conductive properties of ceramics. For improving electrical conductive properties, TiN, TiC and TiB_2 etc. are reinforced into the Si_3N_4 matrix [1,2]. Especially Si_3N_4-TiN is a well-known engineering conductive ceramic composite which is used for high temperature applications such as molten metal handling equipments, gas turbine components, wear-resistant components, aircraft engines. Recently Si_3N_4-TiN composite replaces the copper nozzles in the gas welding process. Machining of Si_3N_4-TiN composite by conventional machining process is very difficult due to its properties mentioned above. EDM is found to be a suitable machining process to machine this Si_3N_4-TiN composite as it has ability to machine any hard materials. EDM is an electro-thermal process which used for machining any kind of electrically conductive materials. EDM is a non contact machining process and it didn't exert significant forces because there is no contact between the work piece and tool [3, 4]. Hence, EDM is a desirable process for machining of ceramic parts without any distortions.

2. Literature Review

Soni et al. [5] have reported that the rotating electrode increase the MRR owing to better flushing and sparking efficiency. However, this results which leads in increase the surface roughness. Dwivedi et al. [6] have proved that better MRR, low recast layer thickness and minimum surface roughness were obtained by using the rotary tool method of EDM. Ghoreishi et al. [7] studied the optimal parameters and compared that vibratory cum rotary EDM yields better MRR, SR and TWR than rotary EDM and vibratory EDM. Dave et al. [8] have revealed that orbital radius along with current has significanon MRR and also there was enhancement in MRR with increase in current and reduction in orbital radius. Aliakbari et al. [9] have involved the tool electrode with an eccentric hole and electrode with two symmetric holes in the rotary EDM. It was found that flushing quality of dielectric fluid was affected while rotating electrode and then the parameters were optimized for optimal responses. Guu et al.[10] have found that the centrifugal force improved the gap flushing and machining efficiency. Rotation of work piece reduced the micro voids on the machined surface. Tamang et al. [11] have produced micro holes of diameter 500μm on SS304 on rotary EDM. Taguchi method was used for optimizing multi- performance characteristics to improve hole quality. Valaki et al.[12] have proved that inner over cut and outer over cut were increased by increase in electrode rotation and inner over cut was comparatively higher than outer over cut at same rotational speed. Ponappa et al. [13] have used rotary tubular tool and analyzed the effects of EDM parameters on micro holes quality in microwave-sintered magnesium nano composites. Eckart Uhlmann et al. [14] have conducted for the drilling of the Si_3N_4-TiN. It was concluded that dry-EDM has obtained higher effective pulse frequency. Selvarajan et al.[15] have analyzed new output parameters of EDM on Si_3N_4-TiN composite and the performance like circularity (CIR), cylindricity (CYL) and perpendicularity (PER) were improved by employing grey relational analysis (GRA) of the Taguchi method. Lauwers et al.[16] have investigated the machinability of three ceramic materials (SiC, B_4C, Si_3N_4-TiN) by using combined strategy of milling-EDM (Roughing) and sink-EDM (finishing). It was revealed that ceramic materials having a low electrical conductivity can still be machined efficiently by good flushing condition of milling-EDM. Qingfeng et al.[17] have introduced a new methodology named as simultaneous EDM and ECM (SEDCM) to compensate TW. And also tool electrode with side-insulation was used to minimize the excessive electrolytic erosion. Finally, it was concluded that dielectric fluid of low-conductivity electrolyte reduced the TW. Liu et al.[18] have analyzed the influences of different discharge pulse shapes in EDM on Si_3N_4–TiN. It was observed that iso-energetic type discharge pulses yield less machining time, better surface quality and good geometry accuracy. Schuberta et al.[19] have proposed an assisting tool electrode method to study the micro EDM erosion behaviors on Si_3N_4-TiN and ATZ (Alumina Toughened Zirconia). The result revealed that MRR, TW, SR and maximum aspect ratio, were influenced by composition of ceramics and discharge energy. Kumar Saxena et al. [20] studied the performance of μ-EDM on conductive SiC ceramic material. It was identified that debris size, resolidified material on machined surface, craters on finished surface were responsible for the surface roughness. Mathan Kumar et al. [21] predicted the EDM behavior on hybrid Al 2618 MMCs and it was seen that MRR and TWR were decreased when increasing the weight percentage of reinforcement materials (Si_3N_4, AlN and ZrB_2). Natarajan et al. [22] conducted experiments on SS304 using tubular brass electrode based with Taguchi method. Jerald et al. [23] have found that open voltage increased the MRR and discharge energy. It was noticed that TW was proportional to current and inversely proportional to machining time. D'Urso and Merla [24] presented the influences of different electrode materials and work piece materials on TWR, OC and conicity in micro EDM. The minimum electrode wear was obtained by tungsten carbide electrode for all the work piece materials. Moreover, copper based electrode had a "damping effect" on the diametrical overcut. Shuliang Dong et al. [25] have developed a new method using multi-diameter electrode with different dielectric fluids in the micro EDM process for improving micro hole quality of Be-Cu alloys. Eventually, surface quality was improved by using multi-diameter electrode and two different dielectric fluids like deionized water and kerosene.

Many researches carried out to improve the performances of EDM in all possible contexts. Rotating electrode method has been highlighted as a better method than sinking method for yielding higher MRR. Rotary electrode has shown positive effects on the performance of the EDM process. Few researches have dealt rotary EDM, sink or stationary EDM with various shape tool electrodes. The best of author knowledge no work has been reported in the exhaustive review regarding the combination method of sinking and rotary method with multi diameter tool electrode. Hence, an attempt has been made to study the effects of combination method (Rotary EDM for I^{st} step minor diameter and Sinking EDM for 2^{nd} step major diameter) on EDM process. The aim of this research work is to optimize the EDM parameters for improving the MRR and hole quality.

3. Experimental Details

Si_3N_4-TiN ceramic composite was selected as work material because of its unique combination of properties like low weight, high specific strength, excellent hardness, oxidation and thermal shock resistance [15]. The composite was procured from a commercial ceramic supplier Saint-Gobain. The size of work piece is a circular disc of 50 mm diameter and 2 mm thickness. The properties of the Si_3N_4-TiN composite are depicted in Table.1.

Table 1. Mechanical and physical properties of Si_3N_4-TiN

Grade	Kersit 601
Chemical composition	Si_3N_4 -- 60 vol % TiN -- 36 vol %
Binder	Al_2O_3 -- 4 vol%
Density (g/cm^3)	3.97
Hardness (kg/mm^2)	1508
Tensile strength MPa	350
Young's modulus (GPa)	340
Fracture toughness (MPa)	5.7
Electrical Resistivity (Ω.m)	7.24×10^{-6}
Thermal conductivity ($Wm^{-1}K^{-1}$)	19

In the proposed work, a copper was used as a tool electrode. Figure 1 display the cylindrical stepped tool having minor and major diameter of the tool are 0.64 mm and 0.70 mm respectively. It was selected to achieve a higher MRR based on reference (Shuliang et al., 2016). The copper stepped tools were manufactured by part programming in the CNC Lathe machine.

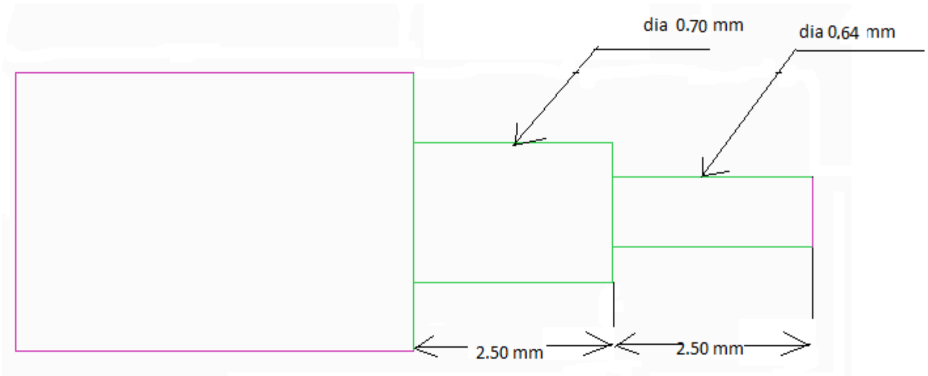

Figure 1. Multi diameter electrode

Based on the exhaustive literatures, pulse current, pulse-on time and method of EDM are chosen as input parameters. The output responses considered are MRR, over cut (OC) and taper ratio (TR) because of its dominated responses in the machining performance of EDM. The selected parameters with its levels are provided in Table 2. Table 3 depicts the minimum number of experiments to be done. L9 orthogonal array is used as a design of experiments which has 3 columns and 9 rows according to Taguchi design in order to reduce the number of experiments.

Table 2. Input parameters and its levels

Symbol	Parameters	Level 1	Level 2	Level 3
A	Pulse current (amps)	0.5	1.0	1.5
B	Pulse-on time (µs)	3	6	9
C	Method of EDM	Sinking (S)	Rotary (R)	Rotary and Sinking (RS)

Table 3. Design of experiment - L9 orthogonal array

Ex.No	A	B	C	Pulse current (amps)	Pulse-on time (μs)	Method of EDM
1	1	1	1	0.5	3	S
2	1	2	2	0.5	6	R
3	1	3	3	0.5	9	RS
4	2	1	2	1.0	3	R
5	2	2	3	1.0	6	RS
6	2	3	1	1.0	9	S
7	3	1	3	1.5	3	RS
8	3	2	1	1.5	6	S
9	3	3	2	1.5	9	R

Experiments were performed by using three methods of EDM processes for investigation of performance characteristics and improvement of MRR, OC and TR on micro hole using stepped electrode. Figure 2(a) shows the micro hole is produced with stepped tool only by sinking method. Similarly, Fig. 2(b) display the micro hole is drilled with stepped tool only by rotary method. Figure 2(c) illustrates the minor diameter step of tool is processed by rotary method and major diameter step of the tool is processed by sinking method.

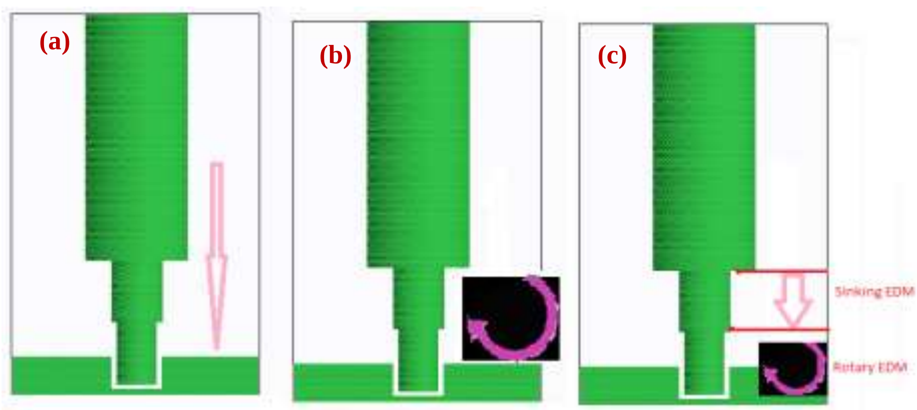

Figure 2. Electrode configuration (a) Sinking electrode method (Step -1 & 2), (b) Rotary electrode method (Step -1 & 2) and (c) Combination Method (Step-1- Rotary and Step-2- Sinking)

Figure 3 shows the Electronica Spark EDM with rotary attachment. A separate rotary attachment is made and attached with the EDM equipment to give the rotary motion to the electrode. The single phase DC motor of 8 kg-m torque is fixed in the conventional EDM. This setup is connected with the ram of die-sink EDM machine. The rotational speed of electrode is varied from 0-300 rpm. Hydrocarbon oil was selected as dielectric fluid.

Figure 3. Electronica Spark EDM

Experiments were done as per the Taguchi L9 orthogonal design. Experiments were repeated by two times in order to minimize the errors. Average values were taken for analysis of results. The work piece and electrodes were cleaned and dried after completion of each experiment. The digital weighing balance (Make- Japan) of accuracy 0.0001g was used to estimate the weight of the work piece and tool electrode before and after machining. The entry side diameters and exit side diameters of the developed holes were measured by using digital optical profile projector as shown in Fig. 4. The diameters at X-axis and Y-axis were measured, then average readings were taken for the calculation.

Figure 4. Digital optical profile projector

Calculation of response parameters such as MRR, OC and TR are as follows:

Calculation of MRR:
MRR was calculated by the weight difference between the work piece before and after machining under a period of time using Eqn. (1).

$$MRR = \frac{Wjb - Wja}{time} \quad (g/min) \qquad (1)$$

where,

W_{jb} - weight of the work piece before eroding (g/min)

W_{ja} – weight of the work piece after eroding (g/min)

Calculation of OC:
The EDM process produces a cavity slightly larger than the electrode size. This excess dimension on the work piece cut by the tool during machining operation is called over cut**.** OC was calculated by substituting the values of average diameters in the Eqn. (2).

$$OC = \frac{Dt - De}{2} \quad (mm) \qquad (2)$$

where,

D_t – hole diameter at entry (mm)

D_e – electrode diameter (mm)

Calculation of TR:
The size of hole at entry and exit are not in same size. Exit hole is somewhat smaller than that of entry hole because of tool wear. Taper ratio can be calculated from the Eqn. (3)

$$\text{Taper ratio} = \frac{Dt - Db}{2H} \qquad (3)$$

Where, D_t - Diameter of the machined hole at the top

D_b - Diameter of the machined hole at the bottom.

H - Height of the work piece is 2 mm.

The input parameters and calculated output responses such as MRR, OC and TR are provided in Table.4.

Table 4. Input Parameters and response values calculated from the experimental data

Ex.No	Pulse current (amps)	Pulse-on time (µs)	Method of EDM	MRR (g/min)	OC (mm)	TR
1	0.5	3	S	0.0002681	0.0315	0.003825
2	0.5	6	R	0.0003711	0.0334	0.003520
3	0.5	9	RS	0.0005834	0.0365	0.003680
4	1.0	3	R	0.0004518	0.0465	0.003420
5	1.0	6	RS	0.0006231	0.0408	0.003150
6	1.0	9	S	0.0002714	0.0340	0.003640
7	1.5	3	RS	0.0006444	0.0457	0.003645
8	1.5	6	S	0.0002867	0.0382	0.004112
9	1.5	9	R	0.0005267	0.0476	0.003675

4. Grey Relational Analysis

The grey relational analysis is used to convert the multi response characteristics which need to be optimized into a single objective [26]. In grey theory, a system can be investigated by means of grey relational grade (GRG). This is used to evaluate the multiple responses. The following steps are taken for calculating the GRG:

Step 1: Signal-to-Noise **(**S/N) ratio was calculated. For EDM process, the maximum MRR and minimum OC and TR are considered as the best performance characteristics. Hence, larger-the-better S/N ratio was chosen for MRR and smaller-the-better S/N ratio was selected for OC and TR by using equation (4) & (5).

$$\text{S/N ratio} = -10\log_{10}(1/n)\sum_{k=1}^{n}\frac{1}{Y_{ij}^{\ 2}} \quad (4)$$

$$\text{S/N ratio} = -10\log_{10}(1/n)\sum_{k=1}^{n}Y_{ij}^{\ 2} \quad (5)$$

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

Step 2: If the performance value is "smaller-the-better characteristics" the original order is normalized as equation (6). If the performance value is "larger-the-better characteristics" the original order is normalized by utilizing equation (7). [26]

$$Y_i^*(k) = \frac{\max Y_i(k) - Y_i(k)}{\max Y_i(k) - \min Y_i(k)}, \quad (6)$$

$$Y_i^*(k) = \frac{Y_i(k) - \min Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad (7)$$

Where Y_i^* (k) - is the data 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 computed S/N ratio and normalized S/N ratio for the MRR, OC and TR are provided in Table 5.

Table 5. 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	-71.4341	30.03379	48.34737	0.000000	1.000000	0.298337
2	-68.6102	29.52507	49.06915	0.273718	0.881988	0.615385
3	-64.6807	28.75414	48.68304	0.837895	0.689441	0.449064
4	-66.9011	26.65094	49.31948	0.488174	0.068323	0.719335
5	-64.1088	27.78680	50.03379	0.943396	0.422360	1.000000
6	-71.3278	29.37042	48.77797	0.008770	0.844720	0.490644
7	-63.8169	26.80168	48.76605	1.000000	0.118012	0.485447
8	-70.8514	28.35873	47.71894	0.049429	0.583851	0.000000
9	-65.5687	26.44786	48.69485	0.687218	0.000000	0.454262

Step 3: The grey relational coefficient (GRC) were calculated from the normalized S/N ratio by using equation (8). [26]

$$\xi_i(k) = \frac{\Delta \min + \zeta \cdot \Delta \max}{\Delta_{0i}(k) + \zeta \cdot \Delta \max} \qquad (8)$$

Where, ζ - is the distinguishing co-efficient, which is defined in the range $0 \leq \zeta \leq 1$. (The present study, ζ - value is taken as 0.5).

Step 4: The grey relational grade (GRG) was getting by an averaging the GRC for each responses and the equation (9) was used. [26]

$$\gamma_i = \frac{1}{m}\sum_{k=1}^{m} \xi_i(k) \qquad (9)$$

Where γ_i - is the GRG for the ith experiment, ξ_i - is the GRC and m – is the number of output responses. Table 6 provided the calculated GRC and GRG with rank.

Table 6. Calculated GRC and GRG with rank

Sl. No	Grey Relational Co-efficient			Grey Relational Grade	Rank
	MRR (ξ_1)	OC (ξ_2)	TR (ξ_3)		
1	0.333333	1.000000	0.41609	0.583141	5
2	0.407736	0.809045	0.565217	0.594000	4
3	0.755168	0.616858	0.475767	0.615931	3
4	0.494156	0.349241	0.640479	0.494625	7
5	0.898305	0.463977	1.000000	0.787427	1
6	0.335294	0.763033	0.495366	0.531231	6
7	1.000000	0.361798	0.492828	0.618209	2
8	0.344692	0.545763	0.333333	0.407929	9
9	0.615171	0.333333	0.478131	0.475545	8

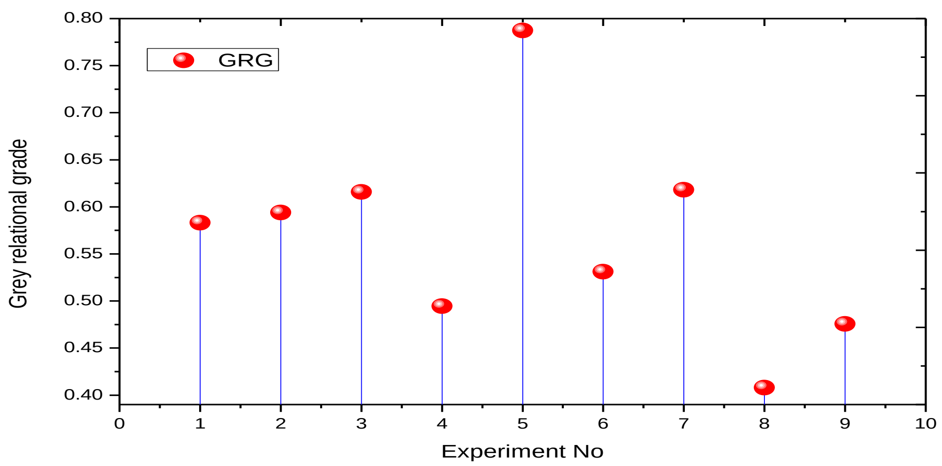

Figure 5. Rank plot for GRG

Figure 5 display the GRG versus experiment number and it was proved that the experiment number 5 has a higher GRG (0.787427), which consists of a optimal EDM parameters (pulse current= 1.0 amps, pulse on-time= 6 µs and method of EDM = RS) with an objective to maximize the MRR and minimize the OC and TR during EDM process of Si_3N_4-TiN composite.

5. Results and Discussions

5.1 Analysis of Machining Parameters on GRG

The mean GRG for each level of the machining parameters and the average mean GRG are depicted in Table 7. The significant of machining parameters was determined by the difference between the highest and lowest value of mean GRG and it is represented as delta (Δ). The maximum value of the delta notices the primarily dominant factor on the output responses. According to the Table 7, it can be understood that the method of EDM has more decisive parameter on combined multiple output responses, subsequently pulse current and pulse-on time respectively. The reason could be the combination of rotary and sinking EDM improves the MRR and also reduces the OC and TR of the machined composites.

Table 7. Response table for mean GRG

Level	Pulse current (A)	Pulse on-time (B)	Method of EDM (C)
1	0.5977	0.5653	0.5074
2	0.6044	0.5965	0.5214
3	0.5006	0.5409	0.6739
Delta	0.1039	0.0555	0.1664
Rank	2	3	1
Average mean grey relational grade = 0.567560			

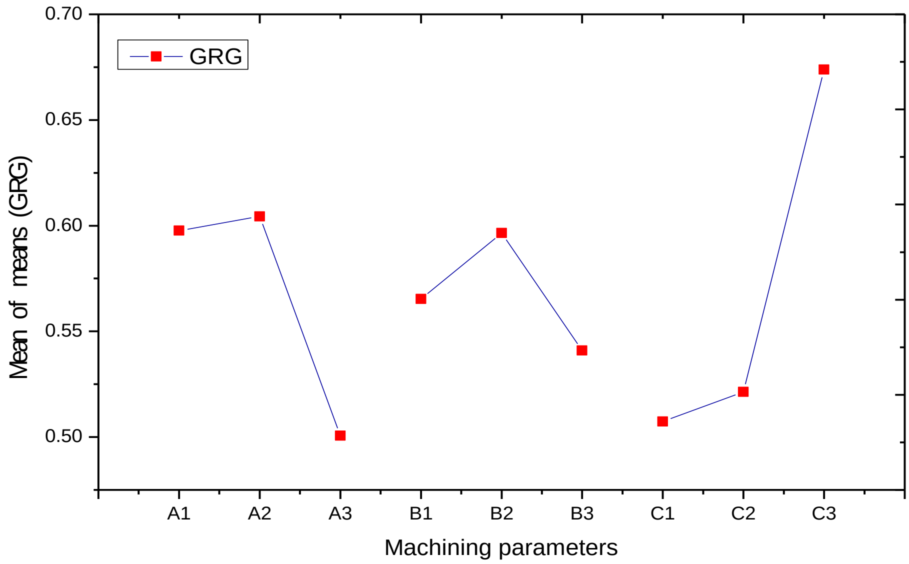

Figure 6. Main effect plot for GRG

Figure 6 shows the effect of machining parameters viz. pulse current, pulse-on time and method of EDM on the mean GRG. From the graph, the largest GRG is closer to the optimum level of parameters. It was clearly revealed that the optimum level of parameters are $A_2B_2C_3$, which indicates that the pulse current at level 2 (1.0 amps), pulse-on time at level 2 (6 µs) and method of EDM at level 3 (RS).

5.2 Analysis of Variance (ANOVA)

ANOVA is used to classify the role of input parameters which statistically significant on the output responses [29]. In proposed study, ANOVA was applied to verify the effects of input parameters such as pulse current (A), pulse-on time (B) and method of EDM (C) on the MRR, OC and TR during EDM process of Si_3N_4-TiN composite. The obtained results from ANOVA analysis are shown in Table 8. From the table, it was noted that the F-ratio value of method of EDM and pulse current were greater than $F_{0.5, 2, 8}$ = 4.46, which also confirms the statistical physical influence on the multiple response characteristics.

Table 8. Analysis of Variance for GRG

Source	DF	Seq SS	Adj SS	Adj MS	F-ratio	% Contribution
Pulse current (A)	2	0.020268	0.020268	0.010134	1.08	21.38
Pulse on-time (B)	2	0.004651	0.004651	0.002326	0.25	4.91
Method of EDM (C)	2	0.051137	0.051137	0.025568	2.75	53.95
Error	2	0.018721	0.018721	0.009360	--	19.75
Total	8	0.094776	--	--	--	--

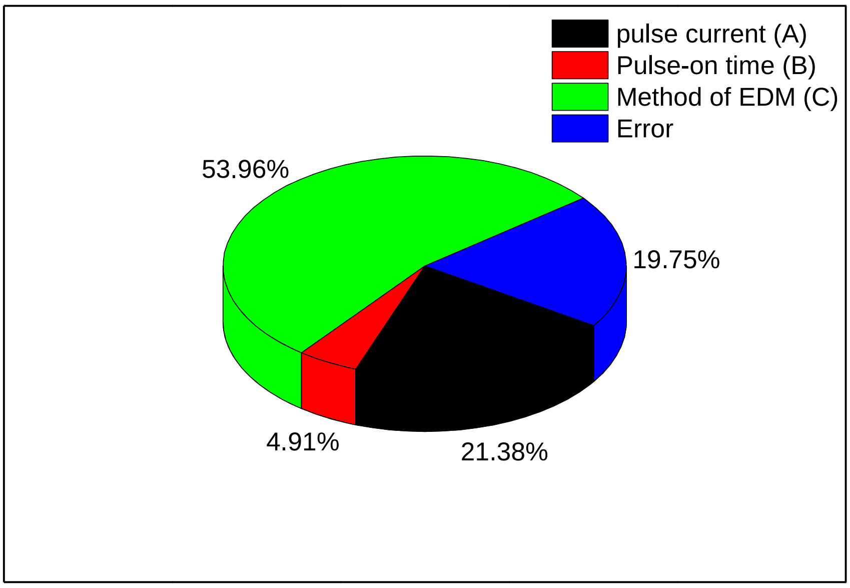

Figure 7. Contribution plot of GRG

Figure 7 display the graphical representation for percentage contribution of each input parameter on the GRG. It was obviously showed that, the method of EDM has the most significant parameter on GRG with contribution of 53.95% followed by pulse current that contributes 21.38% respectively.

5.3 Confirmation Experiments

The confirmation test was performed to validate the experimental results. During the test, the optimum level of machining parameters is used to verify the output responses for EDM process of Si_3N_4-TiN composite. The predicted value of GRG is computed by using equation (10).

$$\eta = \eta_m + \sum_{k=1}^{n} (\eta_i - \eta_m) \quad (10)$$

Where, η- is the predicted GRG, η_m- is the total mean GRG. η_i- is the mean value of the GRG at the optimum level and k- is the number of parameters. The confirmation experimental and predicted results are shown in Table 9.

Table 9. Confirmation Table

Response parameter	Initial level of Machining parameters	Optimum levels of Machining parameters	
		Predicted	Experimental
Level	$A_1B_2C_2$	$A_2B_2C_3$	$A_2B_2C_3$
MRR(g/min)	0.0003711	--	0.0006231
OC(mm)	0.0334	--	0.0408
TR	0.003520	--	0.003150
GRG	0.594000	0.73968	0.787427

6. Conclusions

In the current investigation, EDM process of Si_3N_4-TiN composites was performed and the following conclusions were drawn.

- The grey relational analysis (GRA) was employed to find the optimum level of EDM parameters for the multiple responses with an objective to maximize the MRR, minimize the OC and TR of the composite.
- From the main effect plot revealed that, the optimum level of EDM parameters are pulse current at level 2 (1.0 amps), pulse-on time at level 2 (6 µs) and method of EDM at level 3 (RS).
- From ANOVA results revealed that, the method of EDM was the major significant factor on GRG that contributes 53.95% followed by pulse current at 21.38% respectively.
- The confirmation test was conducted by the optimum level of machining parameters and to validate the predicted results.

References

[1] *Martin, C., Cales, B., Vivier, R. and Mathieu, R. "Electrical Discharge Machine able ceramic composites", Material Science and Engineering:A. vol. 109,* ***(1989),*** *pp.351-356.*

[2] *Bellosi, A., Guicciardi, S. and Tampieri, A. "Development and Characterization of Electro conductive Si_3N_4-TiN Composites", Journal of the European Ceramic Society.vol. 9,* ***(1992),*** *83-93.*

[3] *Goutam Paul, Mitun Das, S., Ghatak, S., Sarkar, Nagahanumaiah, S., Mitra."Investigation on the effect of spark gap in dry μ-electro discharge machining of SiC-10BN nano-composite", Int. J. Manufacturing Technology and Management. , vol. 24,* ***(2011),*** *pp.71-87.*

[4] *Alagarsamy, S.V., Ravichandran, M., Sakthivelu, S., et al. "Optimization of electric discharge machining parameters on surface roughness for Al/ZrO$_2$ cast composite through response surface methodology", Materials Today Proceedings. Vol. 27,* ***(2020),*** *pp.1006-1012.*

[5] *Soni, J.S. and Chakraverti, G. "Machining characteristics of titanium with rotary electro-discharge machining", Wear. vol. 171,* ***(1994),*** *pp. 51- 58*

[6] *Anand Prakash Dwivedi, Member, Iaeng and Sounak Kumar Choudhury. "Comparative assessment of MRR, TWR and surface integrity in rotary and stationary tool EDM for machining AISI D3 tool steel", Proceedings of the World Congress on Engineerin. vol. 2,* ***(2015),*** *pp.1-10.*

[7] *Ghoreishi, M. and Atkinson, J. "A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary", Journal of Materials Processing Technology. vol. 120,* ***(2002),*** *pp. 374-384.*

[8] *Dave, H.K., Desai, K.P. and Raval, H.K. "A Taguchi approach-based study on effect of process parameters in electro discharge machining using orbital tool movement", Int. J. Machining and Machinability of Materials. vol. 13, no. 1,* ***(2013)****, pp.52–66.*

[9] *Aliakbari, E. and Baseri, H. "Optimization of machining parameters in rotary EDM process by using the Taguchi method", Int J. Adv Manuf Technol. vol. 62,* ***(2012),*** *pp. 1041–1053.*

[10] *Guu, Y.H. and Hocheng, H. "Effects of work piece rotation on machinability during electrical discharge machining", Int. Journal of Materials and Manufacturing Processes. vol.16(1),* ***(2001)****, pp. 91-101.*

[11] *Tamang, S. K., Natarajan. N. and Chandrasekaran. M. "Optimization of EDM process in machining micro holes for improvement of hole quality", J Braz. Soc. Mech. Sci. Eng. vol. 39,* ***(2016),*** *pp.1-10.*

[12] *Valaki, J.B., Barot R.S. and Karhadkar. "A comparative experimental study on various response parameters of die sinking edm using stationary and low speed rotary electrode', National Conference on Emerging trends in Mechanical Engineering.* ***(2006),*** *pp. 1-10.*

[13] *Ponappa, S., Aravindan, P. V., Rao and Ramkumar., J. "The effect of process parameters on machining of magnesium nano alumina composites through EDM", Int J Adv Manuf Technol. vol. 46,* ***(2010),*** *pp. 1035-1041.*

[14] *Eckart Uhlmanna, Tassilo-Mari Schimmelpfennig, Ivan Perfilov, Jan Streckenbach and Luiz Schweitzer. "Comparative analysis of dry-EDM and conventional EDM for the manufacturing of micro holes in Si$_3$N$_4$-TiN", Procedia CIRP, vol. 42,* ***(2016),*** *pp. 173 – 178.*

[15] *Selvarajan, L., Sathiya Narayanan, C. and JeyaPaul, R. "Optimisation of EDM parameters on machining Si$_3$N$_4$-TiN composite for improving circularity, pylindricity and perpendicularity", Journal of Materials and Manufacturing Processes. vol. 10.* ***(2015),*** *pp. 1-10.*

[16] *Lauwers, B., Kruth, J.-P. and Brans, K. "Development of technology and strategies for the machining of ceramic components by sinking and milling EDM, Annals of the CIRP. vol. 56,* ***(2007),*** *pp.1-12.*

[17] *Yin Qingfeng, Wang Baorui, Zhang Yongbin, Ji Fang, Liu Guangmin. "Research of lower tool electrode wear in simultaneous EDM and ECM", Journal of Materials Processing Technology. vol. 214,* ***(2014),*** *pp. 1-9.*
[18] *Liu, K., Reynaerts, D. and Lauwers, B. "Influence of the pulse shape on the EDM performance of Si_3N_4–TiN ceramic composite", CIRP Annals - Manufacturing Technology. vol. 58,* ***(2009),*** *pp. 217–220.*
[19] *Andreas Schubert, Henning Zeidler, Ralf Kühn, Matthias Hackert-Oschätzchen, Sebastian Flemmig, and Nico Treffkorn. "Investigation of ablation behaviour in micro-EDM of nonconductive ceramic composites ATZ and Si_3N_4-TiN", Procedia CIRP. Vol. 42,* ***(2016),*** *pp. 727 – 732.*
[20] *Krishna Kumar Saxena, Anand Suman Srivastava and SanjayAgarwal. "Experimental investigation into the micro-EDM characteristics of conductive SiC", Journal of Ceramics International. vol.111,* ***(2015),*** *pp. 1-10.*
[21] *Mathan Kumar, N., Senthil Kumaran, S, and L.A. Kumaraswamidhas. "An investigation of mechanical properties and material removal rate, tool wear rate in EDM machining process of AL2618 alloy reinforced with Si_3N_4, AlN and ZrB_2 composites", Journal of Alloys and Compounds. vol. 650,* ***(2015),*** *pp. 318-327.*
[22] *Natarajan, N., Arunachalam, R.M. and Thanigaivelan, R. "Experimental study and analysis of micro holes machining in EDM of SS 304", Int. J. Machining and Machinability of Materials. vol. 13, No. 1,* ***(2013),*** *pp.1–16.*
[23] *Jerald, J., Kumanan, S., Leo Kumar, S.P. and Chandrakar, H.V. "Experimental investigation and optimisation of process parameters in micro-electrical discharge machining", Int. J. Manufacturing Technology and Management. vol. 27, no. 1/2/3,* ***(2013),*** *pp.88–100.*
[24] *D'Urso, and Merla, C. "Work piece and electrode influence on micro-EDM drilling performance", Journal of Precision Engineering. vol. 38,* ***(2014),*** *pp. 903–914*
[25] *Shuliang Dong, Zhenlong Wang, Yukui Wang, and Hongzheng Liu. "An experimental investigation of enhancement surface quality of microholes for Be-Cu alloys using micro-EDM with multi-diameter electrode and different dielectrics", Procedia CIRP. vol. 42,* ***(2016),*** *pp. 257 – 262.*
[26] *S.V. Alagarsamy and R. Rajesh Kumar. "Parametric optimization for gas metal arc welding process of SS316L and AISI D2 steels by Grey-Taguchi method," Journal of Materials Science Research and Reviews. vol.4, no.3,* ***(2019),*** *pp.1-10.*
[27] *S.V. Alagarsamy and M. Ravichandran. "Parametric studies on dry sliding wear behaviour of A1-7075 alloy matrix composite using S/N ratio and ANOVA analysis", Materials Research Express. vol. 7,* ***(2020),*** *pp. 1-17.*