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Modelling and experimental investigation of process parameters in EDM of Si_3N_4-TiN composites using GRA-RSM[†]

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Abstract

Electric discharge machining (EDM) is a highly promising machining process of ceramics. This research is an out of the paradigm investigation of EDM on Si_3N_4-TiN with Copper electrode. Ceramics are used for extrusion dies and bearing balls and they are more efficient, effective and even have longer life than conventional metal alloys. Owing to high hardness of ceramic composites, they are almost impossible to be machined by conventional machining as it entirely depends on relative hardness of tool with work piece. Whereas EDM offers easy machinability combined with exceptional surface finish. Input parameters of paramount significance such as current (I), pulse on (P_{on}) and off time (P_{off}), Dielectric pressure (DP) and gap voltage (SV) are studied using L_{25} orthogonal array. With help of mean effective plots the relationship of output parameters like Material removal rate (MRR), Tool wear rate (TWR), Surface roughness (Ra), Radial overcut (ROC), Taper angle (α), Circularity (CIR), Cylindricity (CYL) and Perpendicularity (PER) with the considered input parameters and their individual influence were investigated. The significant machining parameters were obtained by Analysis of variance (ANOVA) based on Grey relational analysis (GRA) and value of regression coefficient was determined for each model. The results were further evaluated by using confirmatory experiment which illustrated that spark eroding process could effectively be improved.

Keywords: Electric discharge machining; Surface roughness; Radial over cut; Taper angle; Geometrical tolerances; Ceramic composites

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1. Introduction

Ceramic matrix composite materials find their application in high temperature environments. Experimental investigations on various ceramic materials found that these materials have high strength and hardness. Hence traditional machining processes cannot be employed for the production of complex shapes and may cause cracks on the machined surface. It is also found that their properties lead to less machinability and forms built up edge on the tool. Therefore, at the time of machining, the cutting tool is worn out and it leads to exorbitant tool cost. Eventually, Electrical discharge machining (EDM) process is considered as an ideal method to machine ceramic composites. This underlined the fact that an un-conventional machining process is the best for this kind of application [1-3]. EDM is less expensive and widely used unconventional machining method for good dimensional tolerance in all electrically conductive material even if the materials possess high hardness [4-6]. Though most of the ceramic based composites are non-conductive in nature, conductive ceramic composite materials are also manufactured. Bhduri et al. have proved that the EDM is possible in Titanium nitride-aluminum oxide of ceramic composites. Another such ceramic based composite material is syalon which is composite of Si_3N_4-TiN [7]. Bucciotti et al. investigated the suitability of electro conductive silicon/titanium nitride composite for biomedical implantable devices with particular attention on the processing route that allows the net-shaping of complex components by electrical discharge machining [8].

Ahmad et al. have studied the outcome of electrical and mechanical properties of Si_3N_4-TiN composites. The composites prepared by plasma sintering at 1250-1350 ºC possessed low electrical resistivity and it could be machined by Electrical discharge machining (EDM). In the recent years, the conductive ceramic composites were used in some special applications like level sensors in molten metals, air craft engine and complex moulds for metal forming. From the above literatures, it is clear that the Si_3N_4-TiN ceramic composite together with the EDM manufacturing process might potentially play a key role in the application of engineering materials [9-11].

The selection of suitable electrode plays important role in

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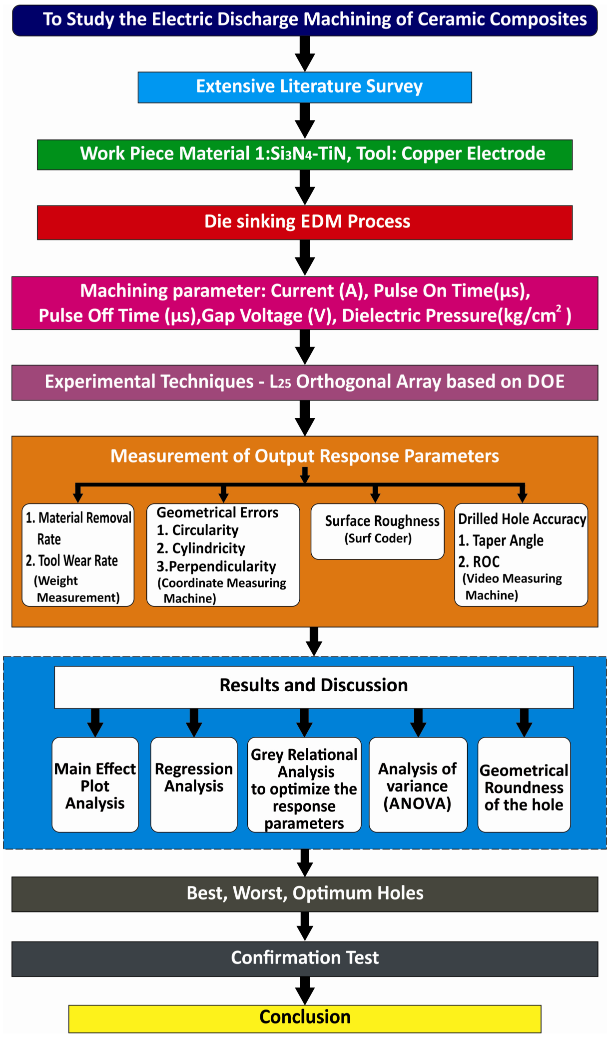


Fig. 1. Research plan.

the EDM process for machining the ceramic composites. Sanchez et al. used solid tool copper electrodes in EDM of TiN–Al_2O_3, Si_3N_4-TiN, B_4C, SiC and found that there was significant improvement in MRR, reduction in tool wear and surface roughness [12]. EDM is usually used to machine any electrically conductive components with less MRR. In EDM, solid cu electrode has been used in machining of ceramic composites for improved efficiency [13]. Therefore, the copper electrode was chosen for this present study.

The dimensions of features that are machined by EDM is important to decide the part accuracy, Patel et al. have studied the influence of EDM parameters such as current, pulse-on time, and dielectric pressure on performance criteria such as MRR, EWR, Overcut and Taper angle during the machining of aluminum-based composites. They concluded that machining performances are affected mostly by current and pulse-on time during the EDM of composite [14].

Recently, Selvarajan et al. conducted an experimental work to evaluate geometrical tolerance in EDM of composites. Standardized design and close tolerances are necessary in manufacturing of parts for applications such as tools, moulds, dies and press work operations. From the literatures available it is observed that only few number of work has been conducted on geometrical tolerance in EDM of ceramic composites hence, in the present work the authors are focused on the geometrical tolerances during electrical discharge machining [15, 16].

Ramanujam et al. used Taguchi technique as an experimental method to reduce the number of experimental trials based on design of experiments. Orthogonal array and optimization techniques are employed to find out the best parameter combinations [17]. Singh et al. used the grey relational analysis method for optimization of the EDM process. Most of the applications of Taguchi method concentrate on the optimization of single response [18]. Chinnaiyan et al. employed the Taguchi method and the Grey relational analysis to optimize the turning operations with multiple response characteristics [19]. So Grey relational analysis can be recommended as a method for optimizing the complicated interrelationships among multiple performance characteristics.

By meticulous study of literature in the field of electric discharge machining of composites it is evident that there has been study about nature of electrodes and work piece affecting the process. Thus the research further focused into investigating each input parameters influence on the hole characteristics. This investigation was possible with help of mean effective plots of each output parameters against all input parameters which were plotted using Minitab. Though many studies have been carried out on EDM process, there is limited experimental works carried out on geometrical tolerances. Thus, this experimental work is attempted to analyze geometrical tolerances in EDM of Si_3N_4-TiN composites.

2. Materials and methods

2.1 Experimental setup

Electrical discharge machining (EDM) was carried out on Si3N_4 using different processing conditions. The work piece was prepared using powder metallurgy techniques. OSCARMAX Spark EDM 600 x 300 series machine was used for experimentation. OSCAR EDMs has high reputation in market for its performance, reliability quality and machining accuracy. The experiments were performed with five factors and five levels as shown in Fig. 2. The work piece material was hot-pressed Si_3N_4-TiN; a composite-grade sialon developed as an electrically conductive ceramic comes from Titanium Nitride. Table 1 elucidates the properties of Si_3N_4-TiN composite materials.

3. Measurements and calculations

There are two kinds of outputs to be measured, process measuring outputs viz. MRR, TWR, SR and dimensional characteristic outputs viz. radial overcut, Taper angle, circularity, cylindricity, perpendicularity. Reduction in weight of the

Table 1. Properties of Si_3N_4-TiN composite.

Properties	Si_3N_4-TiN	
Tensile strength	350	MPa
Young's modulus of elasticity	341	GPa
RT hardness (HRA)	90.5	-
Fracture toughness K^1C	5.7	$MPam^{1/2}$
Poison's ratio	0.31	-
Density	4.01	g/cc
Specific heat	630	J/kg/K
RT thermal conductivity	19.1	W/(mK)
Electrical resistivity	7.24×10^{-6}	Ohm m

Fig. 2. OSCARMAX spark EDM machine.

Fig. 3. Precision electronic balance.

workpiece is calculated by obtaining the weight difference of workpiece, before and after machining using weighing scale as shown in Fig. 3. Machining time is actual time measured for each experiment and reading is taken from the Spark EDM machine. Precision balance was used to measure the weight of the work piece and tool. This machines accuracy is 0.001 grams.

Fig. 4. Surface roughness.

Fig. 5. Video measuring machine.

3.1 Mechanism and evaluation of surface roughness

Surface roughness was measured by surface roughness test machine with an accuracy ±5.5 μm as shown in Fig. 4.

3.2 Mechanism and measurement of over cut

Top and bottom diameter of the drilled hole was measured by Video measuring machine (VMM) with accuracy of 3 microns as shown in Fig. 5.

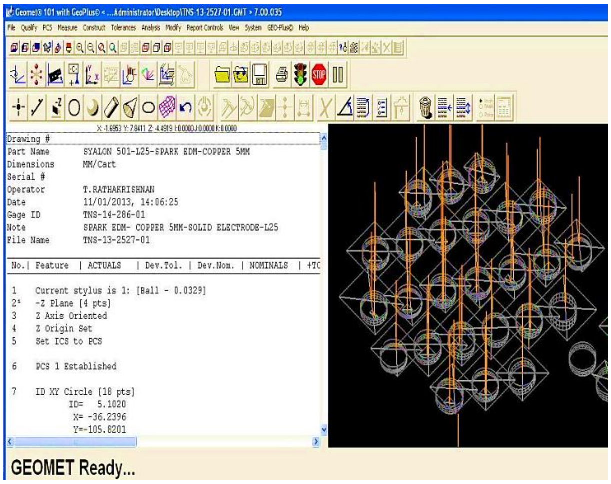
3.3 Measurements and calculations of dimensional characteristics

Circularity, cylindricity and perpendicularity were measured by CMM using GEOMET universal CMM software with an accuracy of 4.5 microns as shown in Fig. 6.

3.4 Experimental responses

The Material removal rate was determined using the Eq. (1).

Fig. 6. Coordinate measuring machine.



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Drawing #
Part Name        SYALON 501-L25-SPARK EDM-COPPER 5MM
Dimensions       MM/Cart
Serial #
Operator         T.RATHAKRISHNAN
Date             11/01/2013, 14:06:25
Gage ID          TNS-14-286-01
Note             SPARK EDM- COPPER 5MM-SOLID ELECTRODE-L25
File Name        TNS-13-2527-01

No.| Feature  | ACTUALS   | Dev.Tol. | Dev.Nom. | NOMINALS  | +TO

1    Current stylus is 1: [Ball - 0.0329]
2*   -Z Plane [4 pts]
3    Z Axis Oriented
4    Z Origin Set
5    Set ICS to PCS

6    PCS 1 Established

7    ID XY Circle [18 pts]
           ID=    5.1020
            X= -36.2396
            Y=-105.8201
```

Fig. 7. Geometrical tolerance measurement of Si_3N_4-TiN composites.

$$\text{MRR (g/min)} = \frac{W_{jb} - W_{ja}}{t} \tag{1}$$

where W_{jb} : Weights of the work piece before machining (g)
W_{ja} : Weights of the work piece after machining (g).

The Tool wear rate (TWR) was determined using Eq. (2).

$$\text{TWR (g/min)} = \frac{W_{tb} - W_{ta}}{t} \tag{2}$$

where W_{tb} : Weights of the tool before machining (g)
W_{ta} : Weights of the tool after machining (g)
t : Machining time (min).

Taper angle was determined using Eq. (3).

$$\theta = \tan^{-1}\left\{\frac{D_{top} - D_{bottom}}{2t}\right\}. \tag{3}$$

Table 2. EDM factors and levels of Si_3N_4-TiN composites.

Parameter	Units	Level 1	Level 2	Level 3	Level 4	Level 5
Current	A	3	4	5	6	7
Pulse on time	µs	4	5	6	7	8
Pulse off time	µs	8	9	10	11	12
Dielectric pressure	kg/cm^2	14	15	16	17	18
Spark gap voltage	V	30	32.5	35	37.5	40

Table 3. Work piece and electrode weight of Si_3N_4-TiN ceramic composites.

Exp No.	Input parameter					Machining time
	Current	Pulse on time	Pulse off time	Dielectric pressure	Spark gap voltage	
	A	µs	µs	kg/cm^2	V	min
1	3	4	8	14	30	27.334
2	3	5	9	15	32.5	22.351
3	3	6	10	16	35	19.301
4	3	7	11	17	37.5	14.284
5	3	8	12	18	40	12.884
6	4	4	9	16	37.5	13.451
7	4	5	10	17	40	11.484
8	4	6	11	18	30	20.484
9	4	7	12	14	32.5	16.934
10	4	8	8	15	35	12.201
11	5	4	10	18	32.5	12.917
12	5	5	11	14	35	11.851
13	5	6	12	15	37.5	9.184
14	5	7	8	16	40	9.751
15	5	8	9	17	30	13.834
16	6	4	11	15	40	9.517
17	6	5	12	16	30	14.901
18	6	6	8	17	32.5	10.984
19	6	7	9	18	35	11.184
20	6	8	10	14	37.5	7.484
21	7	4	12	17	35	12.851
22	7	5	8	18	37.5	6.767
23	7	6	9	14	40	10.251
24	7	7	10	15	30	8.851
25	7	8	11	16	32.5	4.067

Radial overcut,

$$\text{ROC} = \left\{\frac{D_{top} - D_{electrode}}{2}\right\} \tag{4}$$

where $D_{electrode}$: Diameter of a electrode
D_{top} : Top diameter of a drilled hole
D_{bottom} : Bottom diameter of a drilled hole.

Table 4. Experimental response for EDM of Si_3N_4-TiN composite.

Exp No.	MRR	EWR	Ra	ROC	θ	CIR	CYL	PER
	g/min	g/min	mm	mm	deg	mm	mm	mm
1	0.0068	0.0014	0.349	0.062	1.313	0.072	0.072	0.021
2	0.0083	0.0013	0.432	0.0605	0.812	0.063	0.08	0.05
3	0.0091	0.0015	0.478	0.0675	0.726	0.059	0.059	0.025
4	0.0126	0.0017	0.593	0.068	0.783	0.072	0.076	0.033
5	0.0136	0.0016	0.445	0.0595	0.783	0.052	0.059	0.032
6	0.0127	0.0017	0.572	0.0625	0.998	0.073	0.077	0.029
7	0.0152	0.0016	0.349	0.0595	0.697	0.044	0.069	0.044
8	0.0091	0.0013	0.375	0.0575	1.012	0.042	0.072	0.019
9	0.0102	0.0018	0.917	0.0625	1.084	0.054	0.075	0.023
10	0.0141	0.0019	0.441	0.0665	0.955	0.074	0.078	0.036
11	0.0131	0.0015	0.496	0.0655	1.213	0.065	0.066	0.022
12	0.0151	0.0021	0.264	0.071	1.198	0.083	0.104	0.026
13	0.0155	0.0022	0.336	0.064	1.041	0.045	0.057	0.016
14	0.0174	0.0023	0.292	0.172	4.028	0.097	0.123	0.04
15	0.0139	0.0018	0.373	0.074	1.256	0.068	0.05	0.037
16	0.0183	0.0035	0.373	0.1525	3.928	0.05	0.08	0.056
17	0.0113	0.0023	0.629	0.071	1.356	0.096	0.112	0.03
18	0.0165	0.0023	0.222	0.176	3.7	0.076	0.18	0.055
19	0.0163	0.0026	0.593	0.2965	6.824	0.147	0.197	0.181
20	0.023	0.0033	0.133	0.044	0.411	0.059	0.147	0.087
21	0.0143	0.0036	0.205	0.0665	0.783	0.112	0.144	0.053
22	0.0248	0.005	0.574	0.085	2.3	0.103	0.215	0.138
23	0.0183	0.0039	0.448	0.252	6.598	0.173	0.172	0.094
24	0.0192	0.0028	1.257	0.073	2.114	0.067	0.059	0.015
25	0.0428	0.0059	0.345	0.081	-0.792	0.05	0.076	0.211

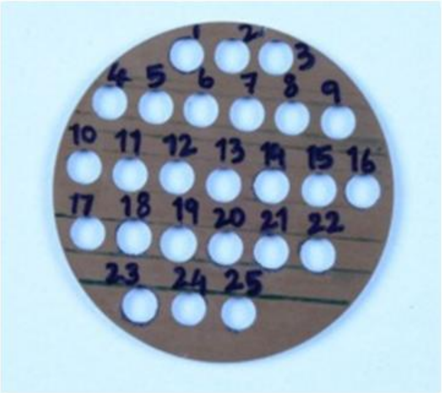

Fig. 8. Si_3N_4-TiN work piece with spark EDM hole.

Video measuring machine was used to capture image of top and bottom diameter and a coordinate measuring machine used for measurement of geometrical tolerance of the drilled hole. The VMM image of all holes are furnished below and their corresponding experimental responses are furnished in the Table 4.

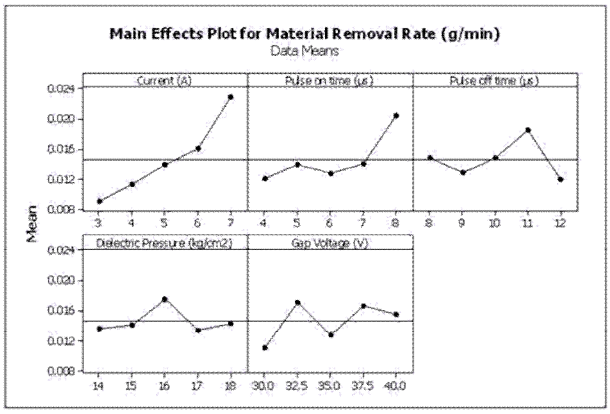

Fig. 9. Main effects plot of material removal rate in Si_3N_4-TiN composites.

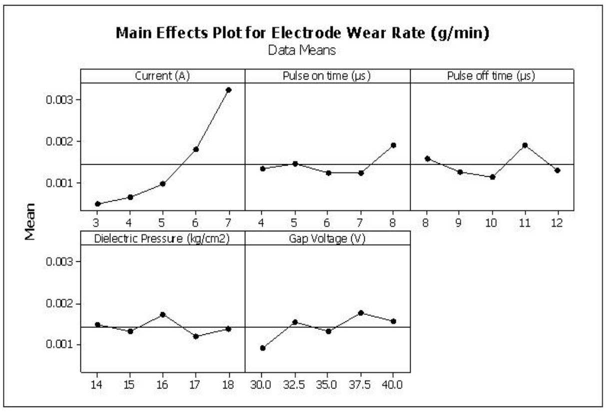

Fig. 10. Main effects plot of electrode wear rate in Si_3N_4-TiN composite.

4. Results and discussions of Si_3N_4-TiN ceramic composites

4.1 Taguchi's analysis for material removal rate

In Fig. 9 the general trend of increase of material removal rate current and pulse on time is shown. Material removal rate can be increased by increasing discharge current, gap voltage and pulse on time. The material removal rate is most significantly affected by discharge current and pulse on time. Whereas there is no significant changewith respect to dielectric pressure.

4.2 Taguchi's analysis for electrode wear rate

In Fig. 10 the general trend of increase of electrode wear with increase in current is shown. Wear rate could be minimized by reducing the discharge current, pulse on time and gap voltage. For any change in di electric pressure and pulse off time there is no significant change in electrode wear rate for this composite material.

4.3 Taguchi's analysis for surface roughness

In Fig. 11 the general trend of decrease in surface roughness

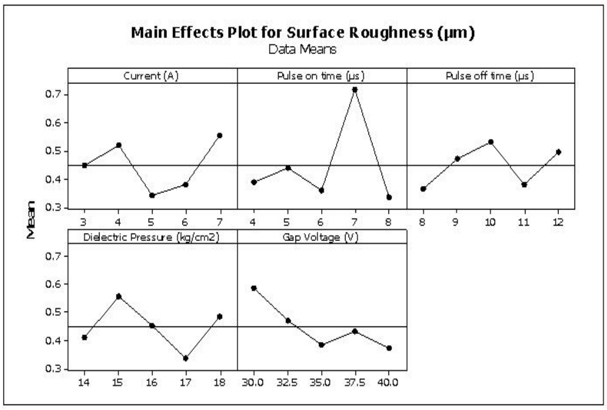

Fig. 11. Main effects plot of surface roughness in Si_3N_4-TiN composites.

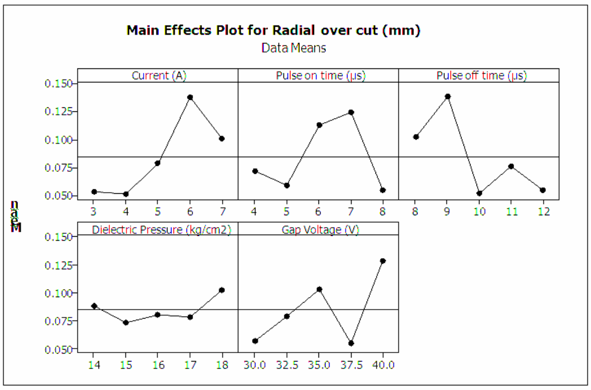

Fig. 12. Main effects plot of radial over cut in Si_3N_4-TiN composites.

with increase in gap voltage is shown. With increase in gap voltage surface roughness decreases in this composite material. Surface roughness can be reduced by moderate discharge current and application of high gap voltage.

4.4 Taguchi's analysis for radial over cut

In Fig. 12 the general trend of increasing radial overcut with increasing current is shown. With respect to gap voltage there is an overall increase in radial overcut. Top radial could be minimized with application of low discharge current, low gap voltage and increasing di electric pressure.

4.5 Taguchi's analysis for taper angle

In Fig. 13 the general trend of increasing taper angle with increasing current is shown. Taper angle could be minimized by reducing discharge current and moderate dielectric pressure.

4.6 Taguchi's analysis for circularity

Fig. 14 elucidates the general trend of circularity increasing with increasing current. Circularity could be minimized by application of low discharge current, low di electric pressure, less gap voltage and high pulse off time.

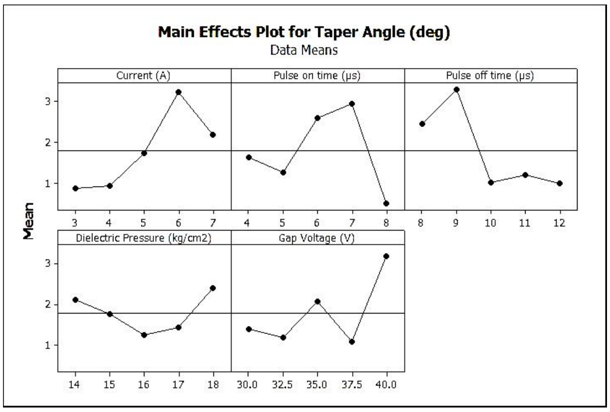

Fig. 13. Main effects plot of taper angle in Si_3N_4-TiN composites.

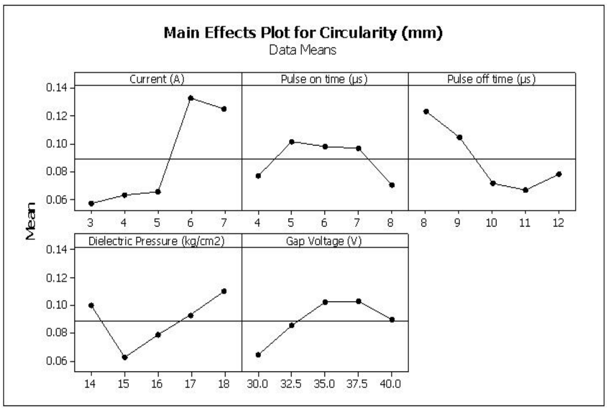

Fig. 14. Main effects plot of circularity in Si_3N_4-TiN composites.

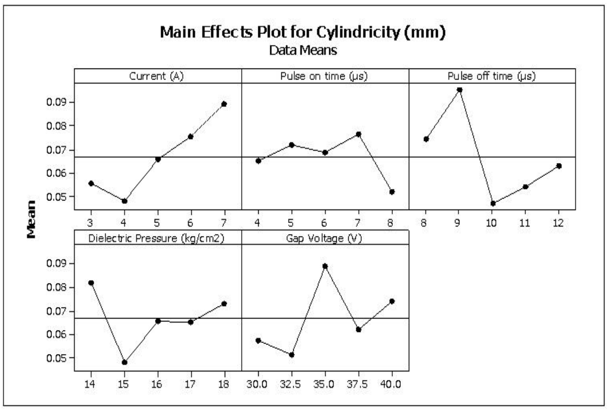

Fig. 15. Main effects plot of cylindricity in Si_3N_4-TiN composites.

4.7 Taguchi's analysis for cylindricity

Fig. 15 shows the general trend of cylindricity increasing with increasing current. Cylindricity could be minimized by application of low discharge current, moderate pulse off time and low di electric pressure.

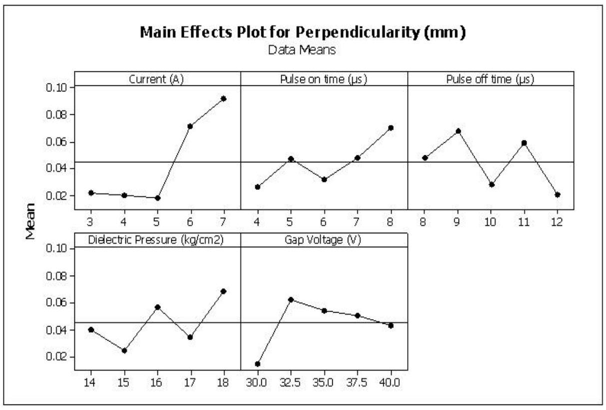

Fig. 16. Main effects plot of perpendicularity in Si_3N_4-TiN composites.

4.8 Taguchi's analysis for perpendicularity

Fig. 16 shows the general trend of increase in perpendicularity with increasing current. Perpendicularity could be minimized by application of low discharge current, low gap voltage and with less pulse on time.

4.9 Results of optimsation by grey relational analysis

The grey-based Taguchi technique is widely used in different fields of engineering to solve multi-response optimization problems. In order to apply the grey-based Taguchi method for multi-response optimization, the following steps are followed:

4.10 Detailed optimization steps using GRA

The Signal-to-noise (S/N) ratio for the relating experimental results is calculated via Eqs. (5) and (6).

i) A higher S/N ratio is better:

$$\text{S/N ratio } (\eta) = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}} \tag{5}$$

where η = the resultant S/N ratio, n = the number of replications, k = number of experiments and y_{ij} = the observed response value, where i = 1, 2... n and j = 1, 2... k. i is the response value in the j^{th} experiment. i = number of responses and j = number of experiments.

In this research, a higher MRR is advantageous. Therefore, Eq. (5) is used to calculate the S/N ratio values of the MRR.

ii) A lower S/N ratio is better:

$$\text{S/N ratio } (\eta) = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_{ij}^{2}\right) \tag{6}$$

where η = the resultant S/N ratio, n = the number of replications, and y_{ij}= the observed response value, where i = 1, 2... n and j = 1, 2... k. i is the response value in the j^{th} experiment. i = number of responses and j = number of experiments.

Lower values of the EWR, surface roughness, radial overcut, taper angle, circularity, cylindricity and perpendicularity are advantageous. Therefore, Eq. (6) is used to evaluate the S/N ratio values of the experimental results. The results are given in Table 5.

Normalisation of the experimental data for each response is completed. Normalisation is often considered a transformation that is carried out by individual data that is entered and can be circulated and measured by a greater analysis, where y_{ij} is normalised as X_{ij} ($0 \le X_{ij} \le 1$) by applying the equation.

$$X_{ij} = \frac{y_{ij} - \min\left(y_{ij}, i = 1,2,\ldots\ldots n\right)}{\max\left(y_{ij}, i = 1,2,\ldots\ldots n\right) - \min\left(y_{ij}, i = 1,2,\ldots\ldots n\right)}$$

(S/N ratio in which a higher value is better) (7)

$$X_{ij} = \frac{\max\left(y_{ij}, i = 1,2,\ldots\ldots n\right) - y_{ij}}{\max\left(y_{ij}, i = 1,2,\ldots\ldots n\right) - \min\left(y_{ij}, i = 1,2,\ldots\ldots n\right)}$$

(S/N ratio in which a lower value is better). (8)

In this work, for maximizing the performance characteristics and for minimizing the performance characteristic Eqs. (7) and (8), respectively, were used to calculate the normalized values of experimental results.

Calculate the Grey relational coefficient (GRC) in normalization experimental results.

$$\gamma\left(y_0(k), y_i(k)\right) = \frac{\Delta\min + \xi\Delta\max}{\Delta_{oj}(k) + \xi\Delta\max}. \tag{9}$$

The defined range of $0 \le \xi \le 1$ determines the differentiate of coefficient. The value can be adjusted on the basis of the functional demand in this technique. The results are given in Table 6.

The grey relational grade $\bar{\gamma}_j$ is calculated by averaging the grey relational coefficients corresponding to each experiment.

$$\bar{\gamma}_j = \frac{1}{k}\sum_{i=1}^{m}\gamma_{ij} \tag{10}$$

where $\bar{\gamma}_j$ the grey relational grade for the j^{th} experiment and '*k*' is the number of performance characteristics. The values for the grey rank provided in Table 6 are plotted at Fig. 12.

Considering the maximisation of the grey rank values, the optimal parameter conditions, $A_5B_4C_2D_5E_5$ are obtained. From the value of grey relational grade in Table 6, using Eqs. (9) and (10), the main effects are tabulated in Table 7 and the factor effects are plotted in Fig. 13.

The optimal parameter for performance are calculated form Grey relational analysis and the result are Current = 7 A, Pulse on time = 7 μs, Pulse off time = 9 μs, Dielectric pressure = 18 kg/cm^2 and Spark gap voltage = 40 V.

Table 5. S/N ratios values of silicon nitride -titanium nitride composites.

Exp. No.	S/N ratio							
	MRR	EWR	Ra	ROC	θ	CIR	CYL	PER
	max	min	min	min	deg	min	min	min
1	-44.7068	67.1511	9.397	25.6809	-2.299	24.1532	24.1532	39.1731
2	-42.7428	71.4235	7.494	25.9352	1.916	23.099	25.5155	27.9598
3	-41.7942	65.7121	6.596	24.8076	2.9	26.1971	26.1971	36.4792
4	-38.7477	63.0974	4.687	24.7324	2.232	24.1532	23.6101	32.7664
5	-38.011	64.1395	7.231	26.1089	2.232	27.536	26.1971	33.1525
6	-38.6023	63.4906	5.006	25.5978	0.103	24.0142	23.4795	34.4259
7	-36.9584	64.3001	9.397	26.1089	3.255	24.584	29.3714	29.3714
8	-41.8792	69.3269	8.755	26.4671	-0.021	24.1532	29.898	40.9161
9	-40.769	61.6531	0.848	25.5978	-0.62	23.7427	27.1319	37.7221
10	-37.6458	60.9003	7.311	24.96	0.489	23.3508	23.8774	31.7015
11	-38.3611	65.3216	6.268	25.1151	-1.604	25.0372	25.1937	38.4174
12	-37.021	59.1965	11.904	24.2944	-1.5	22.7345	20.5384	35.9186
13	-36.7837	58.4328	9.736	25.3531	-0.266	26.559	29.1196	44.438
14	-35.6987	57.5022	10.996	15.8107	-12.08	18.9394	21.2106	30.4586
15	-37.8109	61.9915	8.802	23.8774	-1.909	27.9598	24.7324	31.3737
16	-35.2204	51.9659	8.802	16.9247	-11.861	23.099	27.9598	26.7458
17	-39.7709	57.4441	4.167	24.2944	-2.581	19.829	21.311	33.9804
18	-36.2064	57.8929	13.474	15.5988	-11.34	15.392	23.6101	26.9367
19	-36.3122	55.8667	4.687	10.8585	-16.667	14.5642	17.2666	15.3411
20	-33.1328	52.8735	18.202	29.3714	7.936	17.2666	26.1971	22.2712
21	-37.5191	51.8088	14.2	24.96	2.232	17.4589	19.829	27.3316
22	-32.4711	47.9804	4.975	22.4998	-7.198	13.7659	20.6313	17.8568
23	-35.256	50.6731	7.171	12.3247	-16.374	15.7572	15.8107	21.5154
24	-34.8033	54.8575	-1.916	24.0142	-6.462	24.8835	26.1971	46.0216
25	-27.5754	46.1637	9.5	22.9758	1.916	23.6101	27.9598	13.9371

Table 6. Grey relational co efficient of different trails in Si_3N_4-TiN composites.

Exp. No.	Grey relational co-efficient								Grey grade	Rank
	MRR	EWR	Ra	ROC	θ	CIR	CYL	PER		
1	0.3343	0.3767	0.471	0.3854	0.462	0.4069	0.4588	0.3896	0.4122	25
2	0.3619	0.3343	0.517	0.3814	0.399	0.4329	0.4216	0.5346	0.494	10
3	0.3769	0.3935	0.542	0.3999	0.387	0.3644	0.4051	0.4168	0.4418	22
4	0.435	0.4282	0.604	0.4012	0.395	0.4069	0.4755	0.461	0.4787	14
5	0.4518	0.4137	0.524	0.3787	0.395	0.3411	0.4051	0.456	0.4592	20
6	0.4382	0.4226	0.593	0.3868	0.424	0.4102	0.4798	0.4401	0.468	16
7	0.4782	0.4115	0.471	0.3787	0.382	0.3971	0.3429	0.5107	0.4797	13
8	0.3755	0.3539	0.486	0.3733	0.426	0.4069	0.3343	0.3739	0.4316	23
9	0.3947	0.4502	0.785	0.3868	0.434	0.4167	0.3845	0.4038	0.4504	21
10	0.4606	0.4625	0.522	0.3973	0.418	0.4264	0.4671	0.4755	0.4702	15
11	0.4436	0.3983	0.552	0.3947	0.45	0.3874	0.4298	0.3969	0.465	19
12	0.4766	0.4932	0.422	0.4089	0.448	0.4427	0.5994	0.4229	0.4667	17
13	0.4829	0.5082	0.4643	0.3907	0.429	0.3578	0.3471	0.3457	0.4214	24
14	0.5143	0.5279	0.438	0.6525	0.729	0.5794	0.567	0.4936	0.5486	6
15	0.4566	0.4448	0.485	0.4165	0.455	0.3343	0.4422	0.4802	0.4655	18
16	0.5294	0.6862	0.485	0.6051	0.72	0.4329	0.368	0.557	0.5197	7
17	0.4136	0.5292	0.624	0.4089	0.467	0.5403	0.5625	0.4456	0.4832	12
18	0.4991	0.5195	0.396	0.6623	0.698	0.8146	0.4755	0.5534	0.5744	5
19	0.4961	0.5665	0.604	1.0000	1.0000	0.8999	0.8297	0.9205	0.7511	1
20	0.6075	0.6541	0.334	0.3343	0.334	0.6707	0.4051	0.6591	0.5095	8
21	0.4638	0.6921	0.385	0.3973	0.395	0.6587	0.6377	0.546	0.5078	9
22	0.6373	0.8753	0.594	0.4439	0.566	1.0000	0.5947	0.8046	0.6229	4
23	0.5282	0.7379	0.526	0.8643	0.977	0.7819	1.0000	0.6802	0.6865	2
24	0.5434	0.5933	1.0000	0.414	0.547	0.3906	0.4051	0.3343	0.4927	11
25	1.0000	1.0000	0.469	0.4341	0.399	0.4199	0.368	1.0000	0.683	3

Table 7. Factor effects on grey grade values of Si_3N_4-TiN composites.

Parameter	Grey relational grade					Optimum level	Difference	Rank
	1	2	3	4	5			
Current	0.4572	0.4598	0.4734	0.5676	**0.5986**	5	0.1424	1
Pulse on time	0.5257	0.5159	0.4776	**0.5862**	0.511	4	0.1096	2
Pulse off time	0.5051	**0.546**	0.5249	0.501	0.4796	2	0.0674	5
Dielectric pressure	0.4745	0.5091	0.5111	0.5175	**0.5443**	5	0.0708	4
Voltage	0.4571	0.5334	0.5275	0.5001	**0.5385**	5	0.0825	3

Table 8. ANOVA Analysis of Si_3N_4-TiN ceramic composites.

Factor	SS	DOF	MS	F value	% Contribution
Current	0.0565	4	0.0141	3.810	29.289
Pulse on time	0.0382	4	0.0095	2.567	19.803
Pulse off time	0.0292	4	0.0053	1.432	10.990
Dielectric pressure	0.0260	4	0.0065	1.756	13.478
Gap voltage	0.0362	4	0.0090	2.432	18.766
Error	0.0151	4	0.0037		7.827
Total	0.1929	24			100

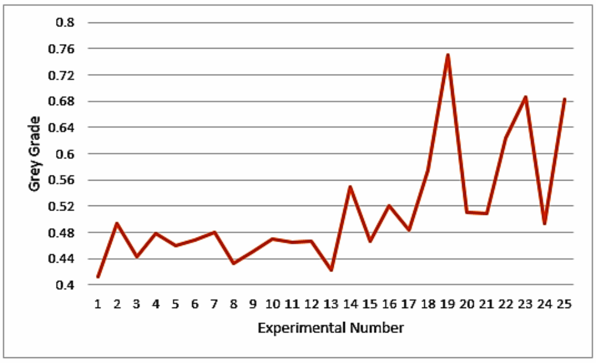

Fig. 17. Grey grade vs experiment number of different trails in Si_3N_4-TiN composites.

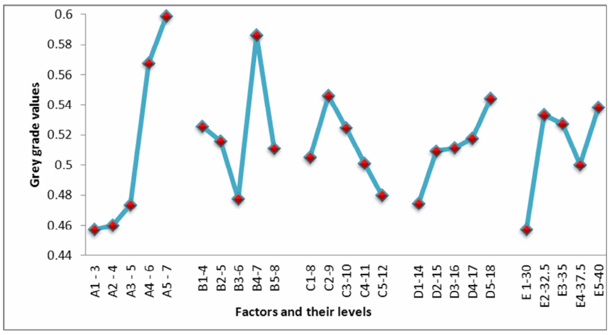

Fig. 18. Factor effects on grey grade values of Si_3N_4-TiN composite.

4.11 Analysis of variance (ANOVA)

ANOVA is performed to identify the significant parameters. The results are given in Table 8.

Using the grey grade value, ANOVA is formulated for identifying the significant factors. From ANOVA, it is clear that current (29.289 %) influences more on sparking followed by pulse on time (19.803 %), spark gap set voltage (18.766 %), di electric pressure (13.478 %) and pulse off time (10.990 %).

Table 9. Comparison of optimsation techniques.

Sl. No.	Response parameter	Machining parameters in 19^{th} trial of OA	Optimsation techniques
			Grey relational analysis
	Setting level	$A_4B_4C_2D_5E_3$	$A_4B_4C_2D_5E_3$
1	Machining time (min)	11.184	9.040
2	Material removal rate (g/min)	0.0163	0.2022
3	Electrode wear rate (g/min)	0.0026	0.0012
4	Surface roughness (μm)	0.593	0.585
6	Radial over cut (mm)	0.296	0.234
7	Taper angle (α°)	6.824	6.558
9	Circularity (mm)	0.147	0.142
10	Cylindricity (mm)	0.197	0.155
11	Perpendicularity (mm)	0.181	0.085
12	Improvement in grade values	0.7511	0.7988

4.12 Verification test

The Grey grade values for multiple performance characteristics in the Sparking EDM process was greatly improved from 0.7511 to 0.7988. Therefore, the exploratory outcome is confirmed by the optimisation of the EDM parameters using the GRA. Grey grade values corresponding to optimal setting selected by optimsation techniques like GRA is listed in Table 9.

4.13 Geometry and roundness of the hole

The image of entry holes and exit holes were captured for the purpose of measuring the form error and they are presented in the figures below. The various images, the value of form error for different holes and the optimized form errors are found to be in a good correlation.

Under different process parameter conditions 25 holes were machined on Si_3N_4-TiN with Spark EDM technique. Image of copper electrode used for each hole after machining is furnished as Fig. 19. The furnished image shows the image of

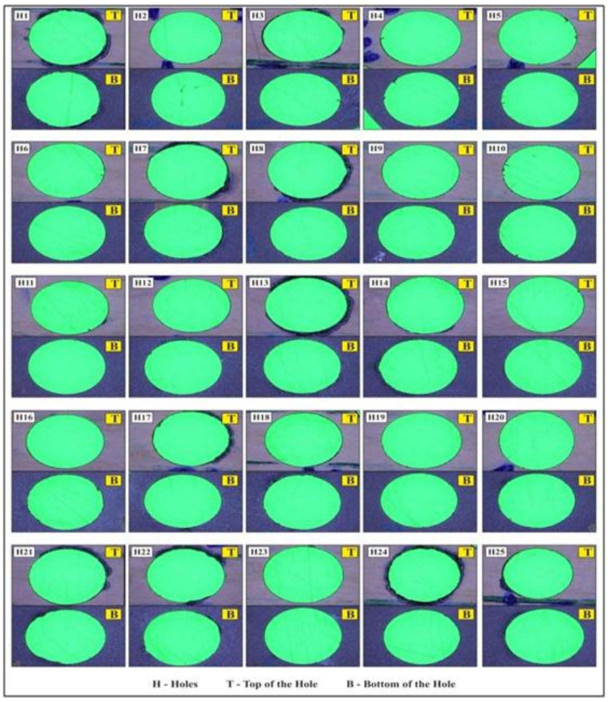

Fig. 19. Top and bottom view of the holes by VMM.

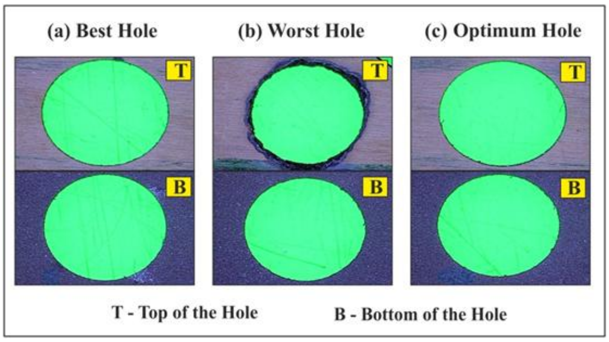

Fig. 20. VMM image of best, worst and optimum hole.

EDM drilled holes on work piece with different parametric combination for 25 holes in Si_3N_4-TiN ceramic composite. These images where obtained by Video measuring machine. The top and bottom images of each set shows geometry of the hole at entry (white shaded) and exit (black shaded). Geometrical tolerances are the major element for fitting any component in assembly. To produce leak proof assembly, the machining process is facing a challenge to produce zero out of circularity. The result of optimization coincides with the video measuring machine image which elucidates that 19th hole is the best parametric combination of top and bottom view of hole image and 24th is the worst hole in parametric combination of top and bottom view taken by Video measuring machine.

The top and bottom surface diameters are measured using VMM and diameters at intermediate positions are measured with the help of Coordinate measuring machine (CMM). Good circularity, surface finish, cylindricity, taper angle, less electrode wear and minimum top and bottom Radial over cut can be clearly seen in the Fig. 20(a). This is because moderate current rate of the order of 6 ampere, pulse on time of the order of 7 micro second, pulse off time 9 micro second, di electric pressure 18 kg/cm^2 and gap voltage of the order of 35 V. When current, pulse on time, dielectric pressure and gap voltage increases and pulse off time decreases, high MRR is obtained by improving the accuracy of the drilled holes.

The irregularities in roundness and Radial over cut can be clearly seen in the Fig. 20(b). This is because high current rate of the order of 3 amperes and gap voltage of the order of 30.0 V, pulse on time of the order of 4 μs , pulse off time 8 μs and dielectric pressure 14 kg/cm^2. When current, gap voltage, pulse on time and pulse off time and dielectric pressure decreases low MRR is obtained. The circularity, cylindricity and perpendicularity are also not maintained from the entry to exit of the hole.

Good circularity, surface finish, cylindricity, taper angle and minimum top and bottom Radial over cut can be clearly seen in the Fig. 20(c). This is because high current rate of the order of 7 amperes, gap voltage of the order of 40 V, high pulse on time of the order of 7 μs, pulse off time 9 μs and Dielectric pressure 18 kg/cm^2 were used during spark EDM. When current, gap voltage, di electric pressure and pulse on time increases and pulse off time decreases high MRR and less electrode wear is obtained thereby improving the accuracy of the drilled holes.

4.14 Regression analysis

To determine output responses at different duty cycle for various Electrodes in EDM of Hot pressed Silicon Nitride - Titanium Nitride ceramics composites. Convectional regression analysis for the purpose of developing each response equation as a function of several inputs process parameters. Once, the input and output variables are identified; then the range of each variable can be determined. The range is given as 0-1. Using design expert software the mathematical models are developed to drive the response equation. The coefficients of regression model can be estimated from the experiment result. The effects of these variables and the interaction between them were included in this analyses and the developed model is expressed as interaction equation.

Estimated regression coefficients for Material removal rate = - 0.258400- 0.013906*C - 0.023832*Pon - 0.002008*Poff + 0.023062*DP + 0.009496V + 0.000733C2 + 0.001440*Pon2 + 0.000625*Poff2 - 0.000730*DP2 - 0.000104*V2 +0.002222*C*Pon - 0.000930*C*Poff +0.000119*C*DP +0.000103*C*V +0.000095*Pon*Dp -0.000133Pon*V -0.000130Poff*V.

Estimated regression coefficients for Electrode wear rate = -0.030453-0.004884*C-0.003416*Pon + 0.000675*Poff + 0.000675*DP + 0.001082*V + 0.000237C2 + 0.000209*Pon2 +0.000075*Poff2 -0.000122*DP2 -

0.000012*V2 +0.000184*C*Pon -0.000144*C*Poff +0.000080*C*DP +0.000063*C*V +0.000046*Pon*DP -0.000017*Pon*V -0.000036*Poff*V.

Estimated regression coefficients for Surface roughness = 5.73178+0.57725*C+0.81207*Pon+1.19304*Poff-1.55358*DP- 0.09010*V+0.04784C2-0.00445*Pon2-0.02522*Poff2+0.04128*DP2+0.00669*V2-0.02536*C*Pon - 0.04015*C*Poff+0.04252*C*DP-0.03474*C*V-0.01053*Pon*DP-0.01394*Pon*V-0.01446*Poff*V.

Estimated regression coefficients for Radial over cut = 0.202313 + 0.031805*C-0.174862*Pon +0.091988*Poff -0.187347*DP +0.072622*V -0.006723C2 -0.011911*Pon2 -0.004593*Poff2 +0.003260*DP2 -0.001092*V2 -0.003219*C*Pon +0.005526*C*Poff-0.003808*C*DP+0.002513*C*V+0.018304*Pon*DP +0.001376* Pon*V -0.001256*Poff*V.

Estimated regression coefficients for Taper angle=51.8609+2.8000*C-2.4615*Pon+4.1056*Poff -7.6581*DP -0.4593*V -0.2140C2 -0.3759*Pon2 -0.2212*Poff2 +0.1636*DP2 +0.0037*V2-0.2877*C*Pon +0.0806*C*Poff -0.0311*C*DP +0.0428*C*V +0.4264*Pon*DP +0.0461*Pon*V-0.0196*Poff*V.

Estimated regression coefficients for Circularity = 0.251783 -0.077612*C -0.060574*Pon +0.047870*Poff -0.109485*DP +0.043704*V +0.000995*C2 -0.005384*Pon^2-0.000867*Poff^2 +0.002321*DP2 -0.000789*V2 -0.002757*C*Pon -0.001609*C*Poff +0.004537*C*DP +0.001484*C*V +0.002891*Pon*DP +0.002693*Pon*V -0.000933*Poff*V.

Estimated regression coefficients for Cylindricity = 0.234130 +0.054552*C -0.125441*Pon +0.101448*Poff -0.288529*DP +0.109154*V +0.001430*C2 -0.003145*Pon2 -0.001766*Poff2 +0.007688*DP2 -0.001165*V2 -0.006815*C*Pon +0.005855*C*Poff -0.003731*C*DP -0.000428*C*V +0.010010*Pon*DP +0.001013*Pon*V -0.003073*Poff*V.

Estimated regression coefficients for Perpendicularity = -0.406895 -0.336429*C -0.238959*Pon +0.142266*Poff -0.124769*DP +0.110092*V +0.006700*C2 +0.005073*Pon^2 -0.002497*Poff^2 +0.001577*DP2 -0.001325*V2 +0.012515*C*Pon -0.000327*C*Poff +0.007771*C*DP +0.002672*C*V +0.008583*Pon*DP -0.000165*Pon*V -0.002388*Poff*V.

In all above equations c denotes current, Pon denotes pulse on time, Poff denotes pulse off time, DP denotes di electric pressure and V denotes gap voltage.

Absolute fraction of variance (R^2) for

MRR removal rate (MRR) = 0.8650
Electrode wear rate (EWR) = 0.9442
Surface roughness (Ra) = 0.6699
Radial over cut (ROC) = 0.720
Taper angle (θ) = 0.7522
Circularity (CIR) = 0.8717
Cylindricity (CYL) = 0.8107
Perpendicularity (PER) = 0.9074.

5. Conclusion

Multi parametric optimization of Si_3N_4-TiN ceramic composites using copper electrode were done using Grey relational analysis approach and the following conclusions are drawn:

(1) The effect on MRR improves when discharge current and pulse on time is increased whereas there is not much influence is observed when pulse off time is increased and there is very little increase improving the fluxing condition.

(2) The EWR increases when discharge current and pulse on time is increased, when gap voltage is decreased whereas there is no significant change when pulse off time and di electric pressure are increased.

(3) The surface roughness decreases when discharge current is decreased whereas on increasing gap voltage surface roughness is observed to be low and there is no significant impact of improving di electric pressure on surface roughness.

(4) The Top radial overcut decreases when current decreases, pulse off time, di electric pressure increases and when gap voltage decreases.

(5) Decreasing taper angle current should be reduced; pulse off time must be increased whereas dielectric pressure and gap voltage should be moderate.

(6) Circularity decreases if current is decreased, di electric pressure and gap voltage is decreased and if pulse off time is increased. Cylindricity is decreased by decreasing current and di electric pressure and applying moderate pulse off time. Perpendicularity is reduced by decreasing current, pulse on time and gap voltage.

(7) The appropriate combination of results has been yielded by factor level settings $A_4B_4C_2D_5E_3$ which resembles 19th experimental parametric combination obtained for grey relational analysis approach.

(8) Results of confirmation test shows that the improvement in grey grade values in grey relational analysis was 0.0454.

(9) The experimental results for optimal settings illustrated that there was a considerable improvement in the Performance characteristics viz., Material removal rate, Tool wear rate, Wear ratio, Surface roughness, Radial over cut, Taper angle, Circularity, Cylindricity, Perpendicularity and Run out, during the spark EDM processes.

References

[1] C. Liu and J. L. Huang, Effect of the electrical discharge

machining on strength and reliability of TiN/Si_3N_4 composites, *Ceramics International,* 29 (6) (2003) 679-687.

[2] R. K. Garg, K. K. Singh, A. Sachdeva, V. S. Sharma, K. Ojha and S. Singh, Review of research work in sinking EDM and WEDM on metal matrix composite materials, *The International Journal of Advanced Manufacturing Technology,* 50 (5-8) (2010) 611-624.

[3] H. S. Shin, M. S. Park, B. H. Kim and C. N. Chu, Recent researches in micro electrical machining, *International Journal of Precision Engineering and Manufacturing,* 12 (2) (2011) 371-380.

[4] R. Ji, Y. Liu, R. Diao, Y. Zhang, F. Wang, B. Cai and C. Xu, Experimental research on electrical discharge machining characteristics of engineering ceramics with different electrical resistivities, *The International Journal of Advanced Manufacturing Technology,* 75 (9-12) (2014) 1743-1750.

[5] G. S. Prihandana, M. Mahardika, M. Hamdi and K. Mitsui, Effect of low-frequency vibration on workpiece in EDM processes, *Journal of Mechanical Science and Technology,* 25 (5) (2011) 1231-1234.

[6] C. Wei, L. Zhao, D. Hu and J. Ni, Electrical discharge machining of ceramic matrix composites with ceramic fiber reinforcements, *The International Journal of Advanced Manufacturing Technology*, 64 (1-4) (2013) 187-194.

[7] D. Bhaduri, A. S. Kuar, S. Sarkar, S. K. Biswas and S. Mitra, Electro discharge machining of titanium nitride-aluminium oxide composite for optimum process criterial yield, *Materials and Manufacturing Processes,* 24 (12) (2009) 1312-1320.

[8] F. M. Bucciotti, Mazzocchi and A. Bellosi, Perspectives of the Si_3N_4 -TiN ceramic composite as a biomaterial and manufacturing of complex-shaped implantable devices by electrical discharge machining (EDM), *Journal of Applied Biomaterials & Biomechanics: JABB,* 8 (2010) 28-32.

[9] N. Ahmad and H. Sueyoshi, Properties of Si_3N_4–TiN composites fabricated by spark plasma sintering by using a mixture of Si_3N_4 and Ti powders, *Ceramics International,* 36 (2010) 491-496.

[10] N. Ahmad and H. Sueyoshi, Microstructure and mechanical properties of silicon nitride–titanium nitride composites prepared by spark plasma sintering, *Materials Research Bulletin,* 46 (3) (2011) 460-463.

[11] N. Ahmad and H. Sueyoshi, Densification and Mechanical Properties of Electroconductive Si 3 N 4-Based Composites Prepared by Spark Plasma Sintering, *SainsMalaysiana,* 41 (8) (2012) 1005-1009.

[12] J. A. Sanchez, L. L. Cabanes, I. de Lacalle and A. Lamikiz, Development of optimum electrodischarge machining technology for advanced ceramics, *The International Journal of Advanced Manufacturing Technology,* 18 (12) (2001) 897-905.

[13] H. K. Yoo, W. T. Kwon and S. Kang, Development of a new electrode for micro-electrical discharge machining (EDM) using Ti (C, N)-based cermet, *International Journal of Precision Engineering and Manufacturing,* 15 (4) (2014) 609-616.

[14] K. M. Patel, P. M. Pandey and P. V. Rao, Optimisation of process parameters for multi-performance characteristics in EDM of Al_2O_3 ceramic composite, *The International Journal of Advanced Manufacturing Technology,* 47 (9-12) (2010) 1137-1147.

[15] L. Selvarajan, C. S. Narayanan and R. Jeyapaul, Optimisation of EDM Parameters on Machining Si_3N_4-TiN Composite for Improving Circularity, Cylindricity and Perpendicularity, *Materials and Manufacturing Processes,* DOI: 10.1080/10426914.2015.1058947 (2015).

[16] L. Selvarajan, C. S. Narayanan and R. Jeyapaul, Optimization of Process Parameters to Improve Form and Orientation Tolerances in EDM of MoSi2-SiC Composites, *Materials and Manufacturing Processes,* DOI:10.1080/10426914.2014.962041 (2014).

[17] R. Ramanujam, N. Muthukrishnan and R. Raju, Optimization of cutting parameters for turning Al-SiC (10p) MMC using ANOVA and grey relational analysis, *International Journal of Precision Engineering and Manufacturing,* 12 (4) (2011) 651-656.

[18] G. K. Singh, V. Yadava and R. Kumar, Diamond face grinding of WC-Co composite with spark assistance: experimental study and parameter optimization, *International Journal of Precision Engineering and Manufacturing,* 11 (4) (2010) 509-518.

[19] P. Chinnaiyan and A. K. Jeevanantham, Multi-objective optimization of single point incremental sheet forming of AA5052 using Taguchi based grey relational analysis coupled with principal component analysis, *International Journal of Precision Engineering and Manufacturing,* 15 (11) (2014) 2309-2316.

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