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ORIGINAL ARTICLE

Optimisation of process parameters for multi-performance characteristics in EDM of Al_2O_3 ceramic composite

K. M. Patel · Pulak M. Pandey · P. Venkateswara Rao

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Abstract The advantages of electrical discharge machining (EDM) in machining of complex ceramic components have promoted research in the area of EDM of ceramic composites. The recent developments in ceramic composites are focused not only on the improvements of strength and toughness, but also on possibilities for difficult-to-machine shapes using EDM. One such EDM-machinable ceramic composite material (Al_2O_3–SiC_w–TiC) has been developed recently and has been selected in the present study to investigate its EDM machinability. Experiments were conducted using discharge current, pulse-on time, duty cycle and gap voltage as typical process parameters. The grey relational analysis was adopted to obtain grey relational grade for EDM process with multiple characteristics namely material removal rate and surface roughness. Analysis of variance was used to study the significance of process variables on grey relational grade which showed discharge current and duty cycle to be most significant parameters. Other than discharge current and duty cycle, pulse-on time and gap voltage have also been found to be significant. To validate the study, confirmation experiment has been carried out at optimum set of parameters and predicted results have been found to be in good agreement with experimental findings.

K. M. Patel (✉) · P. M. Pandey · P. V. Rao
Department of Mechanical Engineering,
Indian Institute of Technology Delhi,
New Delhi 110016, India
e-mail: kaushikmpatel@gmail.com

K. M. Patel
Department of Mechanical Engineering, Institute of Technology,
Nirma University,
Ahmedabad 382481, India

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Nomenclature

A	Discharge current (A)
B	Pulse-on time (μs)
C	Duty cycle
D	Gap voltage (V)
df	Degrees of freedom
l	Number of parameter levels
m	Overall mean S/N ratio
MS	Mean square
MS_e	Mean square of error term
MS_j	Mean square of factor
n	Number of performance characteristics
n	Total number of experiments
q	Number of the machining parameters
R_a	Surface roughness (μm)
SS	Sum of square
SS_e	Sum of squared error
SS_j	Sum of squared deviations for each design parameter
SS_T	Total sum of squares
$x_i\ (k)$	Comparability sequence
$x_0^*(k)$	Reference sequence
$x_i^*(k)$	Sequence after the data pre-processing
γ_i	Grey relational grade
$\widehat{\gamma}$	Estimated grey relational grade
γ_m	Total mean of the grey relational grade
γ_i	Mean of the grey relational grade at the optimal level
η	Signal to noise (S/N) ratio
ρ	Percentage contribution
$\xi_i\ (k)$	Grey relational coefficient

ζ Distinguishing or identification coefficient
$\Delta_{0i}(k)$ Deviation sequence

1 Introduction

Al_2O_3-based ceramics are becoming popular engineering materials because of their excellent mechanical properties, especially its high hardness, wear resistance, high modulus, inertness and refractoriness. The broad range of technological applications presently served by alumina-based ceramics include cutting tool inserts, wire drawing tooling, metal-forming dies, PVC extrusion dies and many more applications. Ceramic composites are of increasing interest with oxide matrices, particularly Al_2O_3 being dominant. Al_2O_3-based ceramic composites are potential substitutes for more traditional materials due to their high hardness, excellent chemical and mechanical stability under a broad range of temperatures and high specific stiffness. The addition of hard, refractory, conductive ceramics such as TiN, TiC, TiB_2 and TiCN in particulate form to Al_2O_3 has been used as an approach to produce composite with high conductivity and improved hardness and toughness. More importantly, the incorporation of these conductive reinforcements makes the composite electrically conductive so that electrical discharge machining (EDM) can be used to shape these materials [1–4].

Recent advances in both electrically conductive ceramic composites and computer-controlled EDM have catalysed extensive research [5–10] into developing spark erosion as the most advanced precision ceramic machining technology. EDM is capable of complex and intricate shaping operations regardless of hardness of material provided its specific electrical conductivity is high enough to support sparking [5]. There have been many attempts to study EDM of Al_2O_3-based ceramic composites [6–10]. Fu and Li [6] selected Al_2O_3–Cr_3C_2 composites for their research work. They observed that the fracture strength and surface roughness of the composites depend strongly on the pulse current and electrical polarity, especially at low energy input. They concluded that the material removal mechanisms of the composites can be categorised as melting at lower pulse current and combined melting and thermal spalling, together with a minor contribution from vaporisation, at higher pulse current. Zhang et al. [7] used a hot-pressed aluminium oxide based ceramic SG4 for EDM. It was experimentally demonstrated that the material removal rate, the surface roughness and diameter of discharge point increases with increasing pulse-on time and discharge current. Zhang et al. [8] attempted to study the surface integrity of EDM of Al_2O_3–TiC–WC ceramic composite and modifying these by ultrasonic polishing. The mean value of flexural strength and the calculated Weibull modulus of ultrasonically polished ceramic specimens were found to be much higher than those of wire EDM processed specimens. Chiang [9] attempted modelling and analysis of the effects of machining parameters on the performance characteristics of EDM process of Al_2O_3–TiC mixed ceramic. The response surface methodology was used to explain the influence of four machining parameters namely discharge current, pulse-on time, duty factor and open discharge voltage on the performance characteristics like material removal rate, electrode wear ratio and surface roughness. Recently, Chiang and Chang [10] employed grey relational analysis to optimise the multi-response characteristics of EDM of Al_2O_3–TiC mixed ceramic.

Kao and Hocheng [11] obtained grey relational grade using grey relational analysis while electrochemical polishing of the stainless steel. Optimal machining parameters were determined by the grey relational grade as the performance index. They observed that the performance characteristics such as surface roughness and passivation strength are improved. Singh et al. [12] suggested that orthogonal array (OA) with grey relational analysis is useful for optimisation of multiple response characteristics which is more complex compared to optimization of single-performance characteristics. They obtained optimal EDM parameters setting of metal removal rate, tool wear rate, taper, radial overcut and surface roughness while EDM of Al–10%SiC_P as-cast metal matrix composites. Chiang and Chang [13] applied grey relational analysis for the optimization of the wire electric discharge machining process of Al_2O_3 particle reinforced material (6061 alloy) with multiple-performance characteristics.

It is evident from the review of literature presented above that the research on spark erosion of Al_2O_3 based ceramic composites has been very limited despite the fact that Al_2O_3 ceramic is attractive material for engineering applications. There is a scope for optimization of various machining parameters using Design of Experiments as most of the studies related to EDM of ceramic composites have used one-factor-at-a-time approach thereby ignoring the effect of interactions among the parameters. An alumina-based ceramic composite has recently been developed by Industrial Ceramic Technology, Inc, USA with sufficiently high electrical conductivity, and can be processed using EDM. The present study is mainly focused on parametric optimisation of EDM-machinable Al_2O_3–SiC_w–TiC ceramic composite using grey relational analysis. From the review of literature, it is observed that grey relational analysis has found wide application areas for determining the optimal parameters for different machining processes [10–13]. In this work, experiments are planned using Taguchi's L_9 orthogonal array and performed by considering discharge current, pulse-on time, duty cycle and gap voltage as typical process parameters. Optimal machining parameters have been determined by the grey relational grade obtained using the grey relational analysis for multiple-performance characteristics namely material removal rate and surface roughness. With the grey relational analysis and analysis of variance (ANOVA) of grey relational grade, the optimal combination of the process parameters has been predicted. Finally, a confirmation test is conducted to validate the optimum process parameters obtained from the analysis of parametric design.

Table 1 Physical and mechanical properties of Al_2O_3–SiC_w–TiC [4]

Density (g/cm^3)	Hardness (Hv)	Fracture toughness ($MPa(m)^{0.5}$)	Thermal conductivity (W/mK at 400K)	Electrical resistivity Ωcm)
3.90	2,400	9.6±0.6	63	0.009

2 Experimental procedure

2.1 Machining parameters selection

A series of experiments were performed on an ELECTRONICA-make die-sinking EDM machine (PS leader ZNC). The electrolytic copper of diameter 8.5 mm was used as an electrode. Commercial-grade kerosene was used as the dielectric fluid and the side injection of dielectric fluid was adopted. A jet flushing system was employed to assure adequate flushing of the debris from the gap zone. The electro-conductive Al_2O_3–SiC_w–TiC ceramic composite was selected as the workpiece, fabricated by hot-pressing at 1,700–1,800°C a mixture of 30.9 vol.% SiC whiskers, 23.0 vol.% TiC powder and balance Al_2O_3. The size of the workpiece is a square of 10×10 mm^2 having thickness 5 mm. The microstructure of the Al_2O_3–SiC_w–TiC ceramic composite has been presented in Fig. 1. Optical microscopy revealed that the Al_2O_3 grains and the TiC particles retained integrity during processing. The SiC whiskers were generally much shorter than when received, probably because of being fractured during milling. The Al_2O_3 grain size was approximately 1 µm and the TiC grain size was approximately 5 µm [4]. The physical and mechanical properties of the Al_2O_3–SiC_w–TiC composite are summarised in Table 1.

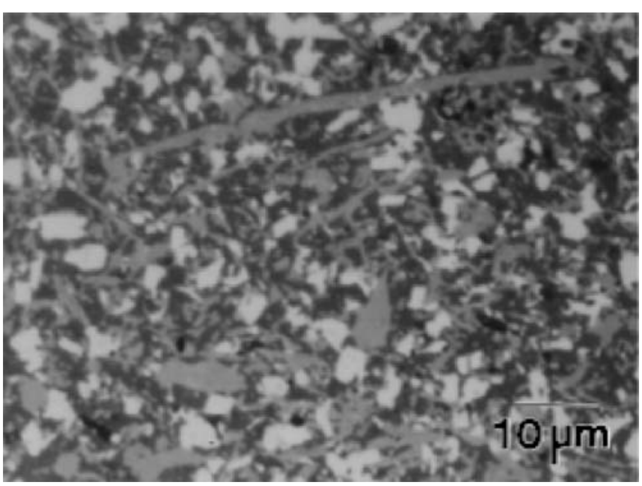


Fig. 1 Optical Micrograph of Al_2O_3–SiC_w–TiC composite, where the bright grains are TiC particles, the *light-grey filaments* are the SiC whiskers, and the *dark-grey background* is the alumina matrix [4]

In this study, the experimental plan has four controllable variables, namely, discharge current, pulse-on time, duty cycle and gap voltage. On the basis of preliminary experiments conducted by using one variable at a time approach, the range of the discharge current, pulse-on time, duty cycle and gap voltage were selected as 3 to 7 A, 50 to 150 µs, duty cycle 0.48 to 0.80 and 50 to 90 V, respectively. At the current less than 3 A, it was observed that material removal rate (MRR) was not so significant and for the current more than 7 A, Al_2O_3–SiC_w–TiC ceramic starts disintegrating because of its low fracture toughness resulting in poor surface finish necessitating the selection of the intermediate values as stated above. The range selected for the pulse-on time was commonly used for the EDM of ceramic composites. The levels selected for the duty cycle cover a wide range of duty cycle. The range of gap voltage selected was in accordance to that available on the machine used for the experimentation. Machining time for each workpiece in the experiments was 60 min. The process variables and their levels are summarised in Table 2.

2.2 Machining performance evaluations

The machining performance evaluated based on the response variables namely MRR and surface roughness. The MRR was calculated based on the weight difference of the workpiece before and after undergoing the EDM process. A high-precision electronic weighing balance (least count$=10^{-4}$ g) was used for this purpose.

Surface roughness measurement was then carried out using a Talysurf 6, Rank Taylor Hobson. A traverse length of 5 mm with a cut-off evaluation length of 0.8 mm was selected. The centre line average value of the surface roughness (R_a) is the most widely used surface roughness parameter in industry is selected in this study. For the efficient evaluation of the EDM process, the MRR and the surface roughness are regarded as "larger-the-better" and "smaller-the-better" characteristics, respectively, in this study.

2.3 Selection of orthogonal array

The orthogonal array with the grey relational analysis is used to determine the optimal machining parameters with considerations of the multiple-performance characteristics. To select an appropriate orthogonal array, total degrees of

Table 2 Machining parameters and their levels

Symbol	Machining parameter	Unit	Level 1	Level 2	Level 3
A	Discharge Current	A	3	5	7
B	Pulse-on time	µs	50	100	150
C	Duty cycle		0.48	0.64	0.80
D	Gap voltage	V	50	70	90

freedom need to be computed. The degrees of freedom are the number of comparisons to be made between design parameters. For example, a three-level design parameter counts for two degrees of freedom. Therefore, in the present work, total degrees of freedom are 9, 8 owing to four parameters with three levels and one for overall mean [14]. Basically, degrees of freedom for an orthogonal array should be greater than or at least equal to number of design parameters. Each parameter was assigned to each column of the orthogonal array. Therefore, only nine experiments were required to study the entire parameter space using L_9 orthogonal array. Normally, the full-factorial design would require (3^4=) 81 experimental runs. However, the effort and experimental cost for such a design could be prohibitive and unrealistic. In the present study, nine experimental runs based on the L_9 orthogonal array with four columns and nine rows is used and is presented in Table 3. The obtained values of MRR and surface roughness are also given in Table 3.

3 Grey relational analysis of the experimental data

The Taguchi method is a systematic application of design and analysis of experiments to improve product quality. In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development also. Most Taguchi experiments are concerned with the optimisation of a single quality characteristic. Antony [15] attempted simultaneous optimisation of multiple quality characteristics in manufacturing processes using Taguchi's quality loss function. The use of Taguchi method with the grey relational analysis can greatly simplify the optimization of process parameters for multiple-performance characteristics [16]. In grey relational analysis, grey relational coefficient for different process characteristics is calculated and average of these coefficients is called grey relational grade which is used as a single response for the Taguchi's experimental plan, and same is illustrated in Fig. 2. Therefore, in the present work, grey relational analysis based on the Taguchi method's response table has been used to optimise EDM of Al_2O_3–SiC_w–TiC ceramic composite for multiple responses namely MRR and surface roughness together.

3.1 Data pre-processing

In grey relational analysis, data pre-processing is required since the range and unit in one data sequence may differ from the others. Data pre-processing is also necessary when the sequence scatter range is too large, or when the directions of the target in the sequence are different. Data pre-processing is a process of transferring the original sequence to a comparable sequence. For this purpose, the experimental results are normalised in the range between zero and one. Depending on the characteristics of data sequence, there are various methodologies of data pre-processing available for the grey relational analysis [16, 17].

Table 3 Experimental layout using an L_9 orthogonal array and performance results

Exp. No.	Level				MRR (g/min)	Surface roughness, R_a (µm)
	Discharge Current (A)	Pulse-on time (D)	Duty cycle (C)	Gap voltage (D)		
1	1	1	1	1	0.000688	2.2785
2	1	2	2	2	0.000895	2.8901
3	1	3	3	3	0.001822	2.6478
4	2	1	2	3	0.001400	1.6472
5	2	2	3	1	0.004097	4.0162
6	2	3	1	2	0.001407	3.5158
7	3	1	3	2	0.003968	3.3016
8	3	2	1	3	0.000985	2.3122
9	3	3	2	1	0.004212	5.1807

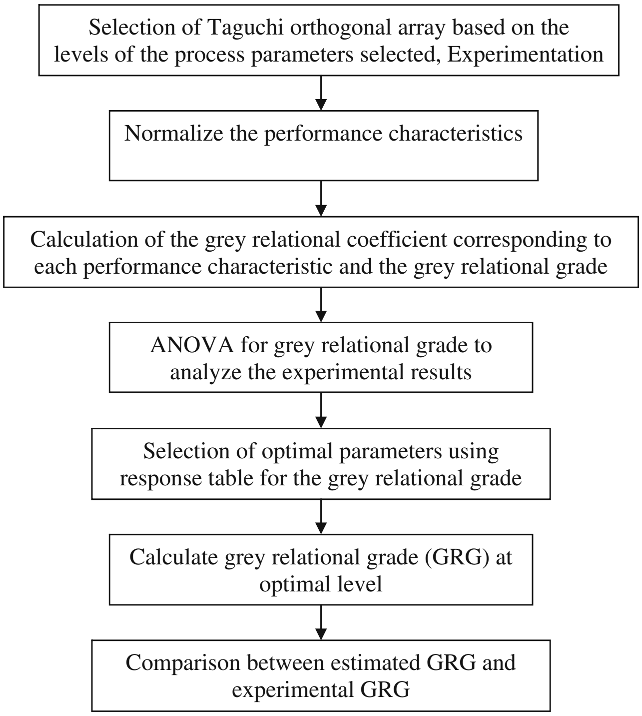


Fig. 2 Grey relational analysis to optimise the process with multiple-performance characteristics

Material removal rate (MRR) is the dominant phenomenon in EDM which decides the machinability of the material under consideration. For the "larger-the-better" characteristic like MRR, the original sequence can be normalised as follows:

$$x_i^*(k) = \frac{x_i(k) - \min\ x_i(k)}{\max\ x_i(k) - \min\ x_i(k)} \tag{1}$$

where, $x_i^*(k)$ and $x_i\ (k)$ are the sequence after the data pre-processing and comparability sequence respectively, k=1 for MRR; i=1, 2, 3…, 9 for experiment numbers 1 to 9 [17].

Table 4 The sequences of each performance characteristic after data processing

Exp. no.	MRR	Surface roughness
Reference sequence	1.0000	1.0000
1	0.0000	0.8213
2	0.0588	0.6483
3	0.3218	0.7168
4	0.2020	1.0000
5	0.9674	0.3296
6	0.2040	0.4712
7	0.9307	0.5318
8	0.0843	0.8118
9	1.0000	0.0000

The surface roughness is also one of the important measures of EDM performance. Selection of optimum process parameters for EDM of Al_2O_3–SiC_w–TiC ceramic composite is at the development stage and their effects on surface roughness have yet to be clarified. To obtain optimal cutting performance, the “smaller-the-better” quality characteristic has been used for minimising the surface roughness. When the “smaller-the-better” is a characteristic of the original sequence, then the original sequence should be normalised as follows:

$$x_i^*(k) = \frac{\max\ x_i(k) - x_i(k)}{\max\ x_i(k) - \min\ x_i(k)} \tag{2}$$

where, $x_i^*(k)$ and $x_i\ (k)$ are the sequence after the data pre-processing and comparability sequence respectively, k=2 for surface roughness; i=1, 2, 3…, 9 for experiment numbers 1 to 9 [17]. All the sequences after data pre-processing using Eqs. 1 and 2 are listed in Table 4.

Now, $\Delta_{0i}\ (k)$ is the deviation sequence of the reference sequence $x_0^*(k)$ and the comparability sequence $x_i^*(k)$, i.e.

$$\Delta_{0i}(k) = \left| x_0^*(k) - x_i^*(k) \right| \tag{3}$$

The deviation sequence Δ_{01} can be calculated using Eq. 3 as follows;

$$\Delta_{0i}(1) = \left| x_0^*(1) - x_i^*(1) \right| = |1.00 - 0| = 1.00$$
$$\Delta_{0i}(2) = \left| x_0^*(2) - x_i^*(2) \right| = |1.00 - 0.8213| = 0.1787$$
$$\text{So, } \Delta_{01} = (1.0000,\ 0.1787)$$

Similar calculation was performed for i=1 to 9 and the results of all Δ_{0i} for i=1–9 are listed in Table 5. Investigating the data presented in Table 5, $\Delta_{max}\ (k)$ and $\Delta_{min}\ (k)$ are obtained and are follows:

$$\Delta_{max} = \Delta_{01}(1) = \Delta_{09}(2) = 1.00$$
$$\Delta_{min} = \Delta_{09}(1) = \Delta_{04}(2) = 0.00$$

Table 5 The deviation sequences

Deviation sequences	Δ_{0i} (1)	Δ_{0i} (2)
Exp. no. 1	1.0000	0.1787
Exp. no. 2	0.9412	0.3517
Exp. no. 3	0.6782	0.2814
Exp. no. 4	0.7980	0.0000
Exp. no. 5	0.0326	0.6704
Exp. no. 6	0.7960	0.5288
Exp. no. 7	0.0693	0.4682
Exp. no. 8	0.9157	0.1882
Exp. no. 9	0.0000	1.0000

Table 6 The calculated grey relational coefficient and grey relational grade for nine comparability sequences

Exp. No.	Grey relational coefficient		Grey relational grade $\gamma_i = \frac{1}{2}(\xi_i(1) + \xi_i(2))$
	MRR ξ_i (1)	Surface roughness ξ_i (2)	
1	0.3333	0.7367	0.5350
2	0.3469	0.5871	0.4670
3	0.4244	0.6399	0.5322
4	0.3852	1.0000	0.6926
5	0.9387	0.4272	0.6830
6	0.3858	0.4860	0.4359
7	0.8783	0.5164	0.6974
8	0.3531	0.7265	0.5398
9	1.0000	0.3333	0.6667

3.2 Computing the grey relational coefficient and the grey relational grade

After data pre-processing is carried out, a grey relational coefficient can be calculated with the pre-processed sequence. It expresses the relationship between the ideal and actual normalised experimental results. The grey relational coefficient is defined as follows [16, 17]:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \cdot \Delta_{\max}}{\Delta_{0i}(k) + \zeta \cdot \Delta_{\max}} \quad (4)$$

Where $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence $x_0^*(k)$ and the comparability sequence $x_i^*(k)$, ζ is distinguishing or identification coefficient. If all the parameters are given equal preference, ζ is taken as 0.5. The grey relational coefficient for each experiment of the L_9 orthogonal array can be calculated using Eq. 4 and same is presented in Table 6.

After obtaining the grey relational coefficient, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple-performance characteristics is based on the grey relational grade, that is:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (5)$$

Where γ_i is the grey relational grade for the ith experiment and n is the number of performance characteristics. Table 6 shows the grey relational grade for each experiment using L_9 orthogonal array. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalised value. Experiment 7 has the best multiple-performance characteristics among nine experiments because it has the highest grey relational grade as shown in Table 6. It can be seen that in the present study optimisation of the complicated multiple-performance characteristics of EDM of Al_2O_3–SiC_w–TiC ceramic composite has been converted into optimisation of a grey relational grade.

Since the experimental design is orthogonal, it is then possible to separate out the effect of each machining parameter on the grey relational grade at different levels. For example, the mean of the grey relational grade for the discharge current at levels 1, 2 and 3 can be calculated by averaging the grey relational grade for the experiments 1 to 3, 4 to 6 and 7 to 9, respectively (Table 7).

The mean of the grey relational grade for each level of the other machining parameters, namely, pulse-on time, duty cycle and gap voltage can be computed in the same manner. The mean of the grey relational grade for each level of the machining parameters is summarised and shown in the multi-response performance index Table 7. In addition, the total mean of the grey relational grade for the nine experiments is

Table 7 Response table for the grey relational grade

Symbol	Machining parameter	Grey relational grade			Main effect
		Level 1	Level 2	Level 3	
A	Discharge current	0.5111	0.6038	0.6346[a]	0.1235
B	Pulse-on time	0.6416[a]	0.5633	0.5447	0.0969
C	Duty cycle	0.5036	0.6088	0.6372[a]	0.1336
D	Gap voltage	0.6282[a]	0.5334	0.5880	0.0948

Total mean value of the grey relational grade=0.5833

[a] Levels for optimum grey relational grade

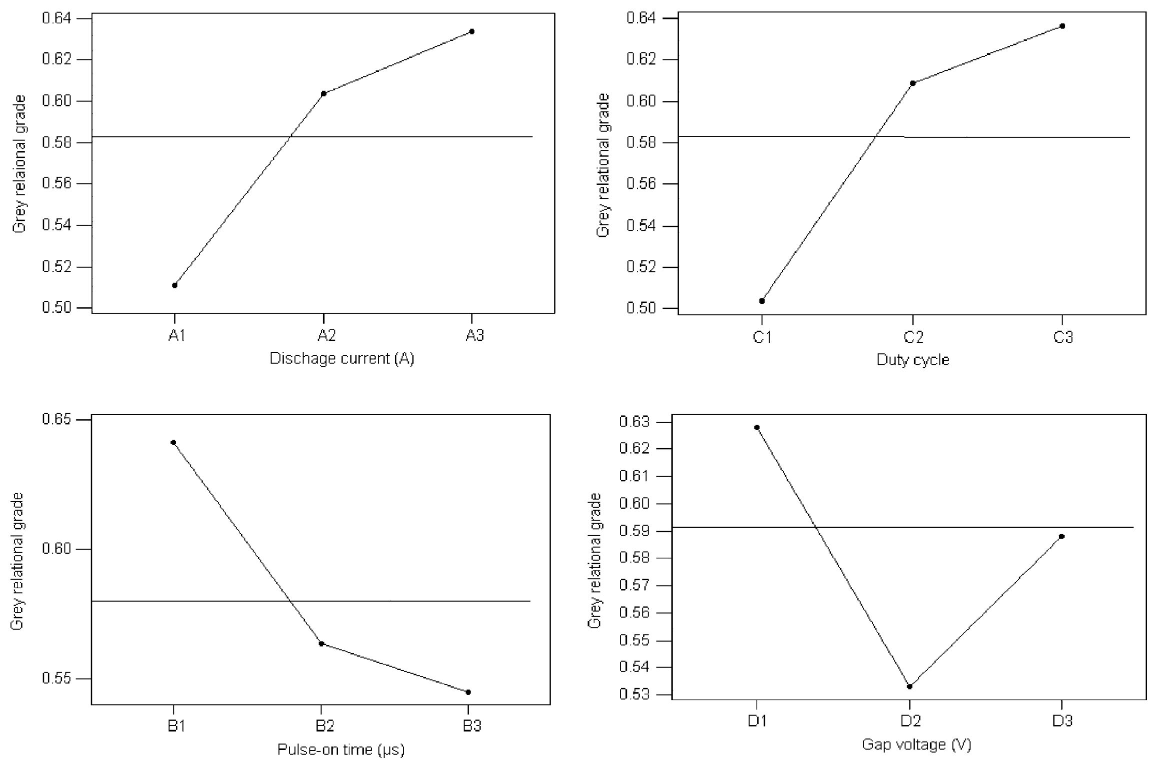


Fig. 3 Effect of EDM parameters on the multi-performance characteristics

also calculated and listed in Table 7. Figure 3 shows the grey relational grade obtained for different process parameters. The mean of grey relational grade for each parameter is shown by horizontal line. Basically, the larger the grey relation grade is, the closer will be the product quality to the ideal value. Thus, larger grey relational grade is desired for optimum performance. Therefore, the optimal parameters setting for better MRR and improved surface quality is ($A_3B_1C_3D_1$) as given in Table 7. Optimal level of the process parameters is the level with the highest grey relational grade. Furthermore, ANOVA has been performed on grey relational grade to obtain contribution of each process parameter affecting the two process characteristics jointly and is discussed in the forthcoming section.

3.3 Analysis of variance

ANOVA is a standard statistical technique to interpret the experimental results. It is extensively used to identify the performance of a group of parameters under investigation. The purpose of ANOVA is to investigate the parameters, whose combination to total variation is significant. In ANOVA, the total sum of squares deviations (SS_T) is calculated by [14, 18].

$$SS_T = \sum_{i=1}^{n} (\eta_i - m)^2 \tag{6}$$

where m is the overall mean S/N ratio.

The total sum of squared deviations, SS_T, is divided into two sources

$$SS_T = \sum_{j=1}^{n_p} SS_j + SS_e \tag{7}$$

where, SS_J is the sum of squared deviations for each design parameter and is given by

$$SS_j = \sum_{i=1}^{l} \left(\eta_{ji} - m\right)^2 \tag{8}$$

Table 8 ANOVA of grey relational grade

Symbol	Machining parameter	*df*	SS	MS	Contribution (%)
A	Discharge current	2	0.0247942	0.0123971	29.52
B	Pulse-on time	2	0.0158858	0.00794292	18.91
C	Duty cycle	2	0.0297282	0.0148641	35.39
D	Gap voltage	2	0.0135923	0.00679614	16.18
Total		8	0.0840006		

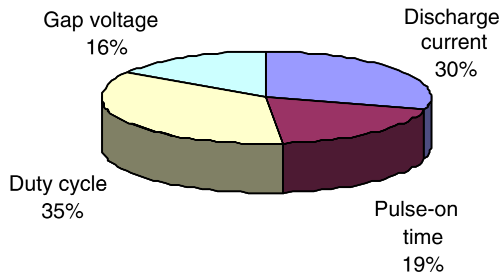


Fig. 4 Percentage contributions of factors on the grey relational grade

where n_p is the number of significant parameters and l is the number of levels of each parameter. SS_e is the sum of squared error without or with pooled factor, which is the sum of squares corresponding to the insignificant factors. Mean square of a factor (MS_j) or error (MS_e) is found by dividing its sum of squares with its degrees of freedom. Percentage contribution (ρ) of each of the design parameters is given by following equation [18].

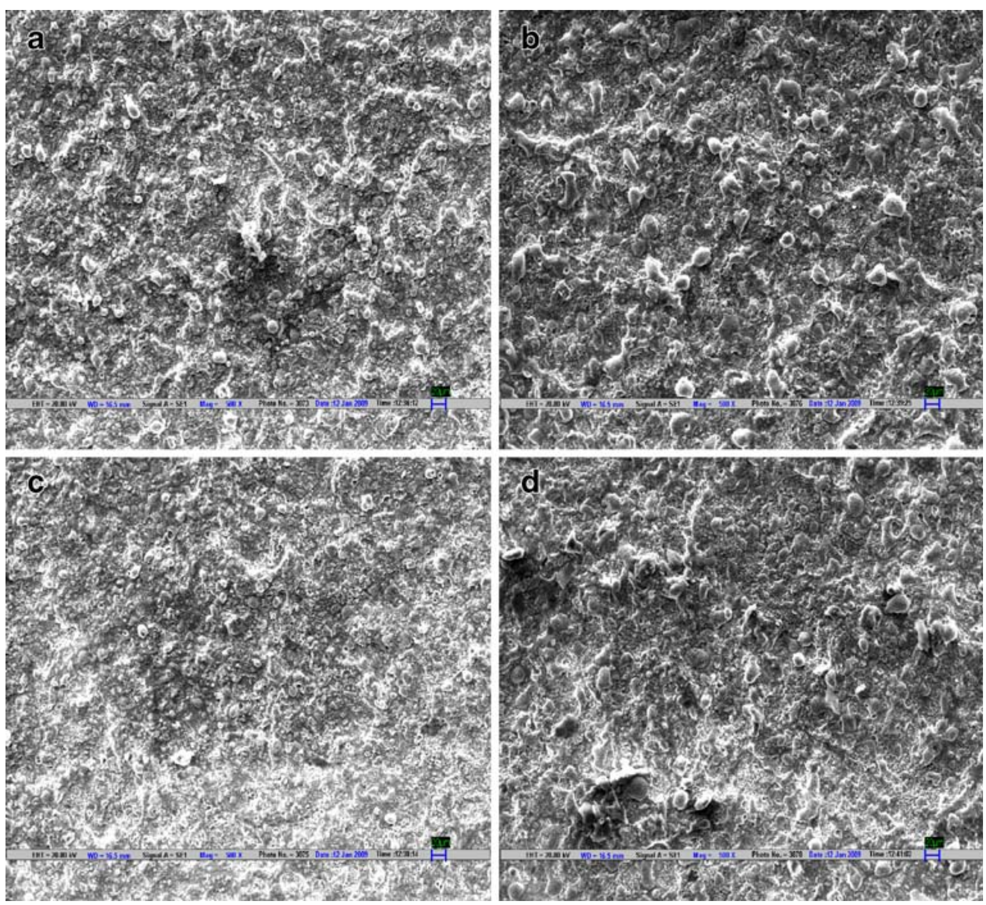
$$\rho_j = \frac{SS_j}{SS_T} \tag{9}$$

ANOVA for grey relational grade is presented in Table 8. Percentage contributions for each term affecting grey relational grade are shown in Fig. 4. The figure clearly shows that discharge current and duty cycle are the two dominant parameters that affect grey relational grade and hence contributes in improving MRR and improving surface quality. Other than discharge current and duty cycle, pulse-on time and gap voltage are also significant. Based on the above discussion, the optimal process parameters are discharge current at level 3, pulse-on time at level 1, duty cycle at level 3 and gap voltage at level 1. Therefore, experiment 7, as shown in Table 3, may be considered as very close to fit the optimal process conditions.

4 Results and discussion

It can be seen from Figs. 3 and 4 that discharge current is the most significant factor that affects the grey relational grade. It has been reported that an increase in discharge current causes an increase in the discharge energy which improves the rate of melting and evaporation and the impulsive force of expanded dielectric medium [19]. The improved melting increases MRR and hence the grey relational coefficient increases. The material removal rate

Fig. 5 EDMed surface characteristics of Al_2O_3–SiC_w–TiC ceramic composite at a duty cycle of 0.64 and a gap voltage 70 V: **a** 3 A, 50 µs, **b** 3 A, 150 µs, **c** 7 A, 50 µs, **d** 7 A, 150 µs



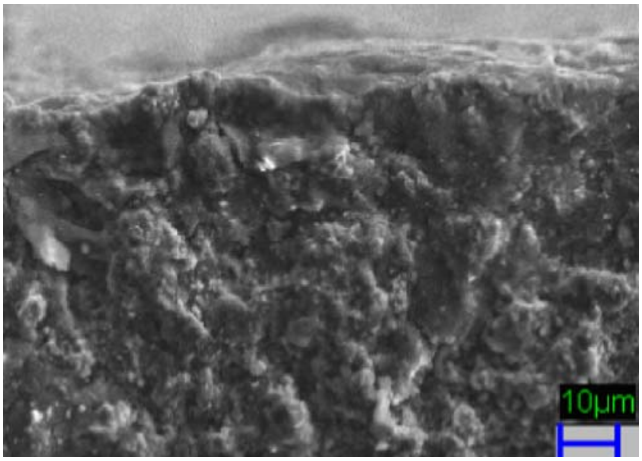


Fig. 6 SEM micrographs shows the formation of the recast layer

in EDM of Al_2O_3–SiC_w–TiC ceramic composite is lesser in comparison to the commonly used workpiece materials like steel. This characteristic is associated with its melting temperature (T_m) and thermal conductivity (K_T) [20]. Al_2O_3–SiC_w–TiC ceramic composite with higher melting temperature, leading to less melting and evaporation, and higher thermal conductivity, causing more heat transfer of discharge energy to the nearby matrix, exhibit a lower MRR in the EDM process.

On the other hand, as the discharge current increases, discharges strike the surface of the workpiece more intensely. The diameter and the depth of craters of EDM-machined surface increase with an increase in the discharge current, and hence the surface roughness consequently increases. The increase in smaller-the-better characteristic surface roughness results in decrease in grey relational coefficient. However, the increase in current results in an increase in grey relational grade. This could be possibly because MRR is more significantly affected by rise in discharge current than surface roughness.

Figures 3 and 4 show that pulse-on time affects the grey relational grade. The value of MRR generally increases with an increase of pulse-on time up to certain level and then decreases with a further increase in the pulse-on time [21]. Large electrical discharge energy and a better peak current density can be reached as the pulse duration increases. The electrical discharge energy conducted into the machining gap within a single discharge period increase with the pulse-on time. Hence, the MRR improves initially with increase in pulse duration. However, the plasma channel may expand with the pulse duration and widens the contact zone of discharging and reduce the peak current density. The energy provided by the plasma channel melts the material, but it is insufficient to generate a high exploding pressure of the dielectric which can flush the molten materials away from the EDMed surface. As a consequence, the molten material cannot be swept away effectively by the circulative dielectric system, and hence the MRR decreases. The development of uneven fusing structures, debris globules, shallow craters, pockmarks and voids were evident with an increase in pulse-on time during EDM of Al_2O_3–SiC_w–TiC ceramic composite. These features give a pitted appearance to the surface. This is also due to the plasma channel expansion with the increase in pulse-on time. The melted debris cannot be removed completely due to reduction in impulsive force and forms an apparent globule-like recasted layer to degrade the surface roughness. This result is in agreement with the surface characteristics shown in Fig. 5. Therefore, a decrease in grey relational grade is observed with an increase in pulse-on time. Subsurface damage and recast layer of the EDMed specimens were also investigated and are presented in Fig. 6. When the spark eroded area was observed for subsurface damage, formation of recast layer was observed. The extremely fine cracks have been filled by the recast layer.

It is clear from Figs. 3 and 4 that duty cycle is the most significant factor that affects the grey relational grade. With an increase in duty cycle, MRR increases and surface roughness decreases which increase grey relational grade. The increase of the duty cycle means applying the spark discharge for longer duration and this will cause an increase in the amount of melted material removal. The value of surface roughness decreases with duty cycle. This allows

Table 9 Comparison between machining performance using the initial and optimal level

	Machining parameters in ninth trial of OA	Machining parameters in 7th trial of OA	Optimal machining parameters	
			Prediction	Experiment
Setting level	$A_3B_3C_2D_1$	$A_3B_1C_3D_2$	$A_3B_1C_3D_1$	$A_3B_1C_3D_1$
Material removal rate (g/min)	0.004212	0.003968	0.004877	0.004279
Surface roughness, R_a (μm)	5.1807	3.3016	3.8909	3.3885
Grey relational grade	0.6667	0.6974	0.7921	

Improvement of the grey relational grade=0.1254 applying the heat for a shorter cycle time and containing lower pressure energy. The machined surface has more fine pockmarks, which decreases the surface roughness.

Figures 3 and 4 show that gap voltage is the significant factor that affects the grey relational grade. With an increase in gap voltage, both surface roughness and MRR increase which results into reduction of grey relational grade. However, beyond a certain value of gap voltage, grey relational grade increases. This may be due to improvement in the surface finish with an increase in the gap voltage.

5 Confirmation test

Confirmation test has been carried out to verify the improvement of performance characteristics while EDM of Al_2O_3–SiC_w–TiC ceramic composite. Optimum parameters are selected for the confirmation test as given in Table 7. The estimated grey relational grade $\widehat{\gamma}$ using the optimal level of the machining parameters can be calculated using following equation.

$$\widehat{\gamma} = \gamma_m + \sum_{i=1}^{q} (\gamma_i - \gamma_m) \qquad (10)$$

where γ_m is the total mean of the grey relational grade, γ_i is the mean of the grey relational grade at the optimal level, and q is the number of the machining parameters that significantly affects multiple-performance characteristics.

The obtained process parameters, which give higher grey relational grade, are presented in Table 9. The predicted MRR, surface roughness and grey relational grade for the optimal machining parameters are obtained using Eq. 10 and also presented in Table 9. Table 9 also shows the comparison of experimentally obtained MRR and surface roughness of a trial which gives maximum MRR (trial 9 of the OA) and experimentally obtained MRR and surface roughness at optimum EDM process parameters. It can be seen that the overall performance of EDM process has been improved. Though the improvement in MRR is not significant, surface roughness has been significantly reduced from 5.1807 to 3.3885 µm.

6 Conclusions

The grey relational analysis based on the Taguchi method's response table has been proposed as a way of studying the optimization of EDM process parameters for Al_2O_3–SiC_w–TiC ceramic composite. Optimal machining parameters have been determined by the grey relational grade for multi-performance characteristics that is material removal rate and surface roughness. Nine experimental runs based on Taguchi method's orthogonal arrays have been performed. Following conclusions can be drawn from this study.

1. The work successfully evaluated the feasibility of EDM of newly introduced ceramic composite Al_2O_3–SiC_w–TiC. The material removal rate is quite low in EDM of Al_2O_3–SiC_w–TiC. However, the surface finish obtained is such that further finishing is not required. The material selected for the study is robust for electric discharge machining.
2. From the response table of the average grey relational grade, it is found that the largest value of grey relational grade for discharge current, pulse-on time, duty cycle and gap voltage 7 A, 50 µs, 0.80 and 50 V, respectively. These are therefore the recommended levels of controllable process factors when better MRR and lower surface roughness are simultaneously obtained.
3. The ANOVA of grey relational grade for multi-performance characteristics revealed that the discharge current and duty cycle are the most influential parameters.
4. It was evident from the above study that optimization of the complicated multiple-performance characteristics can be greatly simplified through Taguchi and grey relational analysis approach. It is shown that the performance characteristics of the EDM process such as material removal rate and surface roughness are improved together by using the method proposed by this study. The effectiveness of this approach has been successfully established by validation experiment.

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