Parameter optimisation of powder mixed EDM of aluminium-based metal matrix composite using Taguchi and grey analysis

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Parameter optimisation of powder mixed EDM of aluminium-based metal matrix composite using Taguchi and grey analysis

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Abstract: Powder-mixed electrical discharge machining (PMEDM), a non-conventional manufacturing process involves the use of a dielectric fluid mixed with abrasive powder (Al_2O_3), combines the benefits of mechanical and thermal interactions. The aim of this article is to use a new approach of performance evaluation to evaluate the effectiveness of optimising multiple performance characteristics of PMEDM of SiC reinforced ZA-27 metal matrix composites (MMCs). Taguchi analysis is used to plan and analyse the experiment and grey relational analysis (GRA) for multi-parameter analysis. The considered process parameter includes the four control factors namely powder concentration, % Sic in MMC, pulse current (I_p) and duty cycle (τ). The combination of L_9 orthogonal array design of experiment with GRA enables to determine the optimal parameters for multiple responses. GRA is used to obtain a single performance index, grey relational grade through grey relational coefficient to optimise the PMEDM process. In addition, analysis of variance (ANOVA) for the GRC is also utilised.

Keywords: metal matrix composites; MMCs; powder-mixed electrical discharge machining; PMEDM; grey relational analysis; GRA; multiple responses, optimisation; orthogonal array.

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1 Introduction

The new concept of manufacturing uses non-conventional energy sources like sound, light, mechanical, chemical, electrical, electrons and ions. With the industrial and technological growth, development of harder and difficult to machine materials which find wide application in aerospace, nuclear engineering and other industries owing to their high strength to weight ratio, hardness and heat resistance qualities has been witnessed. New developments in the field of material science have led to new engineering metallic materials, composite materials and high tech ceramics having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity. Non-traditional machining has grown out of the need to machine these exotic materials. The machining processes are non-traditional in the sense that they do not employ traditional tools for metal removal and instead they directly use other forms of energy. Currently, non-traditional processes possess virtually unlimited capabilities except for volumetric material removal rates for which great advances have been made in the past few years to increase the material removal rates. As removal rate increases, the cost effectiveness of operations also increase, stimulating ever greater uses of non-traditional process. The electrical discharge machining process is employed widely for making tools, dies and other precision parts. In this process the metal is removing from the work piece due to erosion case by rapidly recurring spark discharge taking place between the tool and work piece. Syed and Kuppan (2013) have discussed the effect of aluminium powder when mixed in the distilled water dielectric fluid. Prihandana et al. (2009) presented a new method that consists of suspending micro-MoS 2 powder in dielectric fluid and using ultrasonic vibration during μ-EDM processes. The Taguchi method is adopted to ascertain the optimal process parameters to increase the material removal rate of dielectric fluid containing micro-powder in μ-EDM using a L 18 orthogonal array (OA). Singh and Bhardwaj (2011) also experimented and concluded that electrode material had a greater influence on properties and composition of surface layer. Mir et al. (2012) have explained parametric optimisation of surface roughness (SR) study on the powder-mixed electrical discharge machining (PMEDM) of H11 steel has been carried out. Sharma et al. (2012) found that for Inconel 600 on EDM the multi performance optimisation result which affect significantly the machining characteristics are pulse current, voltage and pulse duration. Shabgard and Shotorbani (2009) have developed hot die material widely used in forging dies manufacturing and carried out to analyse the effects of machining parameters in respect of listed technological characteristics.

In this study, an attempt has also been made to determine the most effective process parameter according to the order of importance and parameter optimisation of PMEDM using Taguchi and grey analysis is attempted.

1.1 Concept of EDM

Electro-discharge machining (EDM) is an electro-thermal non-traditional machining process where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive. A thin gap about 0.025 mm is maintained between the tool and work piece by a servo system shown in Figure 1. Both tool and work piece are submerged in a dielectric fluid.

Figure 1 Set up of powder mixed electric discharge machine (see online version for colours)

This Figure 1 shows the electric setup of the electric discharge machining. The tool is made cathode and work piece is anode. When the voltage across the gap becomes sufficiently high it discharges through the gap in the form of the spark in interval of ten of micro seconds and positive ions and electrons are accelerated, producing a discharge channel that becomes conductive. When the spark jumps causing collisions between ions and electrons and creating a channel of plasma a sudden drop of the electric resistance of the previous channel allows that current density reaches very high values producing an increase of ionisation and the creation of a powerful magnetic field. The moment spark occurs sufficiently pressure developed between work and tool as a result of which a very high temperature is reached and due to high pressure and temperature some part of metal is melted and eroded. Such localised extreme rise in temperature leads to material removal. Material removal occurs due to instant vaporisation of the material as well as due to melting. The molten metal is not removed completely but only partially.

This process of melting and evaporating material from the work-piece surface is in complete contrast to the conventional machining processes, as chips are not mechanically produced. The volume of material removed per discharge is typically in the range of 10^{-6} to 10^{-4} mm^3. Since the shaped electrode defines the area in which the spark erosion will occur, the accuracy of the part produced after EDM is fairly high. In which the form of the electrode is mirrored in the work piece.

2 Literature review

The literatures on EDM are categorised under three major headings. The first relates to machining performance measures such as material removal, tool wear and surface quality (SQ) and also surveys on them. The second area describes the effects of process parameters including electrical and non-electrical variables which are required to optimise the stochastic nature of the sparking process on the performance measures. Finally, research concerning the design and manufacturing of electrodes is reported. A significant number of papers have been focused on ways of yielding optimal EDM performance measures of high MRR, low tool wear rate (TWR) and satisfactory SQ.

Several researches have explained the material removal mechanism (MRM) in terms of the migration of material elements between the work piece and electrode. Soni and Chakraverti (1996) have shown an appreciable amount of elements diffusing from the electrode to the work piece and vice versa. Roethel et al. (1976) has described about the elements that are transported in solid, liquid or gaseous state and alloyed with the contacting surface by undergoing a solid, molten or gaseous-phase reaction. The types of eroded electrode and work piece elements together with the disintegrated products of dielectric fluid significantly affect the MRM relating to the three phases of sparking, namely breakdown, discharge and erosion Erden (1983). In addition, Gangadhar et al. (1992) have clarified regarding the reversing the polarity of sparking alters the material removal phenomenon with an appreciable amount of electrode material depositing on the work piece surface.

Other ways of explaining the MRM have also been reported by different authors. Singh and Ghosh (1999) have shown that the electrostatic forces and stress distribution acting on the cathode electrode were the major causes of metal removal for short pulses. Gadalla and Tsai (1989) have attributed the material removal of WC-Co composite to the melting and evaporation of disintegrated Co followed by the dislodging of WC gains which have a lower electrical conductivity. However, Lee and Lau (1991) have argued that thermal spalling also contributes to the MRM during the sparking of composite ceramics due to the physical and mechanical properties promoting abrupt temperature gradients from normal melting and evaporation. Bayramoglu and Duffill (1994) have successfully experimented and investigated the machining characteristics of contour machining with simple cylindrical electrodes. Bleys et al. (2002) have referred the novel machining technique to (MEDM) which eliminates the need of producing and storing various types of 3D electrodes for different kinds of work piece shapes. Wong and Noble (1986) have introduced more complex motions to the cylindrical electrode by using a micro-computer controlled XY table. Kobayashi et al. (1992) have investigated the effects of suspended powder in dielectric fluid on MRR and SR. It was reported that the surface finish of SKD-61 material gets improved with the use of silicon powder. Yan and Chen (1994) have studied the effect of suspended aluminium and silicon carbide powders on EDM of SKD11 and Ti-6Al-4V. It was observed that the MRR improves considerably whereas the SR increases. Ming and He (1995) have reported that the additives (conductive and inorganic oxide particles) increase the MRR, decrease the TWR and improve the SQ of the work piece quite effectively, especially in mid-finish machining and finish machining phases. Mir et al. (2012) observed that SR improves when aluminium powder is added into the dielectric fluid of EDM. Also Parkash and Kumar (2013) found in their research that TWR is higher with copper as an additive and less when graphite is used in the dielectric. Syed and Kuppan (2013) experimented and investigated that when Al powder is added to the dielectric with increase in concentration of powder the white layer thickness of recast layer decreases for any value of peak current. Sharma et al. (2012) studied that machining characteristics like MRR and TWR improves by using powder in the dielectric. Bhattacharya et al. (2012) experimented on powder mixed EDM for H11 hot die steel and calculated the stresses generated due to thermal loading. Periyanan et al. (2013) focused on the Taguchi optimisation methodology which is applied to optimise cutting parameters in micro-end milling operation when machining aluminium block with carbide end mill cutter. Rehman and Babu (2009) have explained concept of RMS although started at the machine level has now spread to almost all the components of the manufacturing systems. Emerging technologies in the form of machine tool, material handling, tooling, automation etc., guide the reconfiguration exercise. A number of configurations are considered while making the change, guided either by local factors or in rare cases, by optimisation models. Mukherjee and Ray (2009) have tried to compare and contrast the solution quality as determined by genetic algorithm and tabu search for process improvement methodology. Kumar et al. (2011) have discussed the quality of interaction amongst different subsystems, sub-subsystems and other factors that affect the quality of products. These are modelled using graph theory and matrix algebra as quality graph, quality matrix and quality permanent function of the electroplating product. A number of analytical tests derived from these models help to carry out optimum selection of qualities of subsystems and interactions for designing competitive electroplating products.

Although so many literatures have explained regarding general EDM but less researches are found in powder EDM. So the objective is set to work on powder EDM.

3 Experimental details

The experiment of electrical discharge machining was conducted by using an integrated type EDM (G-30i model, TOOLCRAFT, India) with a spark generator (A-25 model, TOOLCRAFT, India). In the present work ZA27 alloy having chemical composition of 25 to 28 wt% Al, 2 to 2.5 wt% Cu, 0.01 to 0.02 wt% Mg and a balance of zinc, in accordance with ASTM B 669-82 ingot specification is used as the matrix alloy. Silicon carbide (SiC) with a particle size (90–120 μm) is used as the reinforcement material. The weight percentage of SiC was varied with 0%, 3% and 6%. A stir casting technique is used to prepare the composite specimens. In this process, the matrix alloy (ZA27) was superheated above its melting temperature (i.e., about 800°C) and stirring is carried out to ensure the even temperature distribution, then the SiC particle were introduced into the molten alloy. Thereafter, the temperature was raised gradually and stirring was continued to promote the wetting at the particulate-matrix interface. The melt with SiC particle was then poured into a permanent mould and allowed for solidification. The surfaces of the samples are polished with sand paper prior to experiment.

3.1 Design of experiment

In order to determine the effects of process parameters on the performance measures, all the experiments were planned based on DoE. The DoE methodology included the identification of process parameters of the powder mixed EDM process. Henceforth, in this study four processing parameters were chosen at three levels each. The specific levels were assigned on the basis of the preliminary experiments.

The process parameters considered are abrasive powder concentration, APC (g/L), work material composition (%SiC), pulse current, I_p (A), pulse ON/OFF time (μs) with three levels each. The responses considered are MRR (g/min), TWR (g/min) and SR, Ra (lm). The factors and levels used in this experimentation are shown in Table 1.

Table 1 EDM machining factors and their levels

Serial no.	*Process parameters*	*Level-1*	*Level-2*	*Level-3*	*Units*
A	Powder (Al_2O_3) concentration in dielectric	1	2	4	g/l
B	Material composition (SiC%)	0	3	6	%
C	Pulsed current (I_p)	4.5	6	7.5	A
D	Duty cycle (τ)	0.5000	0.3300	0.2857	-

3.2 Experimental procedure

Blind hole drilling were performed, using the solid copper electrode according to the L_9 OA on the selected composite (ZA27/SiC MMC) material. The machining time was noted for each experiment and a single trial was performed. The detail of the experimental work was carried out as follows:

Step 1 First the work piece is grinded by grinder of grit size 80 an then by 120 for smoother work surface. the grinder wheel is of specification (diameter × thickness × inner) 350 mm × 25 mm × 18 mm. For smoother surface finish sand paper of grit size 120 and then for further smoother finish 240 grade grit papers is used. After getting desired surface finish, the job piece is cut in to pieces of dimension 3.7 mm × 2.4 mm.

Step 2 Here after the work piece is machined using set of settings as in OA L_9. An extra set up is taken inside the dielectric container for this experiment.

Step 3 For each experiment the work piece and the tool were weighed before and after the drilling operation using an electronic balance and the mass of work piece material and tool removed were calculated. The machining operation time was recorded using an electronic timer. MRR for each experiment was calculated using the following expression:

$$MRR = \frac{\text{initial mass of workpiece} - \text{final mass of workpiece}}{\text{machining time}} \quad (1)$$

TWR was calculated using the following expression:

$$TWR = \frac{\text{initial mass of electrode} - \text{final mass of electrode}}{\text{machining time}} \quad (2)$$

After each experiment, the SR of the machined work piece surface was measured using a stylus type SR tester (TAYLOR HOBSON SURFACE METER). The calculated values for each experiment are tabulated as per Table 2.

Table 2 Experimental layout using $l_{9\ an}$ OA and multi performance result

Exp. no.	*Powder concentration (A), g/l*	*Percentage of SiC reinforced (B), %*	*Pulsed current (C), A*	*Duty cycle (D),τ*	*MRR, g/min*	*TWR, g/min*	SR *Ra, µm*
1	1	0	4.5	0.5	0.21	0.0118	3.04
2	1	3	6	0.33	0.0706	0.000867	3.47
3	1	6	7.5	0.2857	0.1248	0.009667	2.84
4	2	0	6	0.2857	0.0458	0.008267	2.1
5	2	3	7.5	0.5	0.155533	0.0092	4.16
6	2	6	4.5	0.33	0.150267	0.003867	5.02
7	4	0	7.5	0.33	0.003201	0.008411	3.29931
8	4	3	4.5	0.2857	0.057321	0.003836	5.00654
9	4	6	6	0.5	0.183479	0.007092	6.833

Step 4 Then the work pieces were etched with solution of natal (dehydrated ethyl alcohol (C_2H_5OH) and concentrated nitric acid (HNO_3), 10% v/v). The post-etched work pieces were again polished with fine-grade emery paper.

Step 5 After getting completely smooth surface the specimens were kept under the electronic microscope which was interfaced to the computer through a data cable.

4 Result and discussion

The Taguchi method is statistical method developed by Genichi Taguchi to improve the quality of manufactured goods. OA and S/N ratios are two main components of the Taguchi method. An OA is used to reduce testing time cost. On the analysis side, Taguchi advocated the S/N ratio as a single indicator that jointly and simultaneously considers the average value and standard deviation of test results to determine the relative importance of the factors under study. The S/N ratio can be categorised into three types as follows. Selection of the appropriate S/N ratio depends on the features of responses.

1 the smaller-the-better (STB) type

$$SN_{STB} = -10\log_{10}\left(\frac{1}{t}\sum_{1=1}^{m} y^2(i)\right) \tag{3}$$

2 the larger-the-better (LTB) type

$$SN_{LTB} = -10\log_{10}\left(\frac{1}{t}\sum_{1=1}^{m}\frac{1}{y^2(i)}\right) \tag{4}$$

3 the nominal-the-better (NTB) type

$$SN_{NTB} = 10\log_{10}\left(\frac{1}{t}\sum_{i=1}^{m}\left(y(i)-v\right)^2\right) \tag{5}$$

In the above-mentioned equations, m, $y(i)$ and i the number of mixtures, the testing result of the i^{th} test and the target value of the response respectively.

In the present work, the Taguchi method is used to determine optimal machining parameters to maximise MRR and minimise TWR and SR of EDM process. The method uses OA and calculates signal to noise (S/N) ratios. In addition to this a statistical analysis of variance (ANOVA) is also employed to indicate the impact of process parameters. Here S/N ratio for MRR is LTB, for TWR is LTB and for SR is LTB is calculated.

4.1 Taguchi analysis: MRR versus conc., %sic, I_p, τ

Using the software MINITAB the response table for MRR is generated in Table 3.

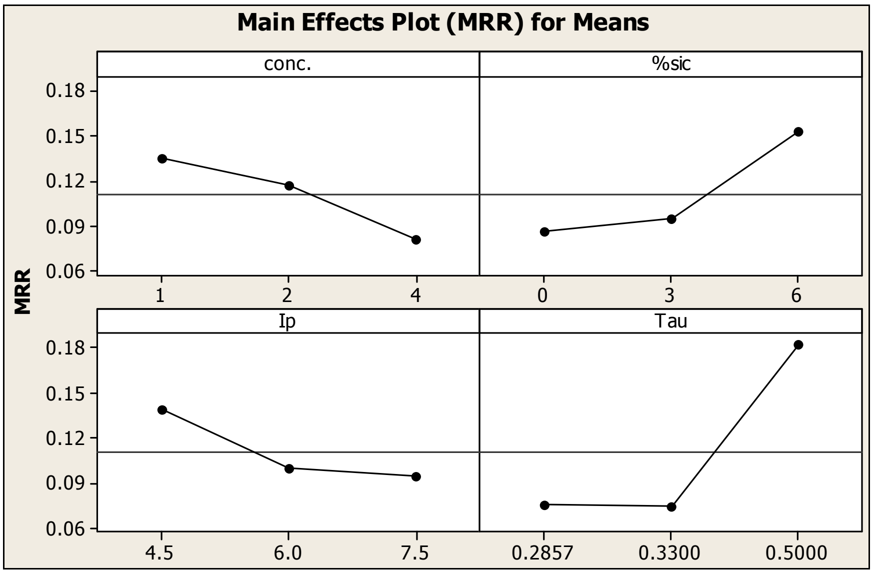
Table 3 Response for MRR

Level	*Conc.*	*%SiC*	I_p	*T*
1	0.13513	0.08633	0.1392	0.07597
2	0.1172	0.09448	0.09996	0.07469
3	0.08133	0.15285	0.09451	0.183
Delta	0.0538	0.06651	0.04468	0.10831
Rank	3	2	4	1

The control factor with the greatest influence was determined by the difference between the maximum and minimum value of each parameter and calculated as delta in ranking of predominant parameters influencing the MRR using mean values obtained for different parameter levels are listed in Table 3. It can be observed from these tables that duty cycle was the most dominant parameter influencing the MRR. The main effect plot for MRR is shown in Figure 2.

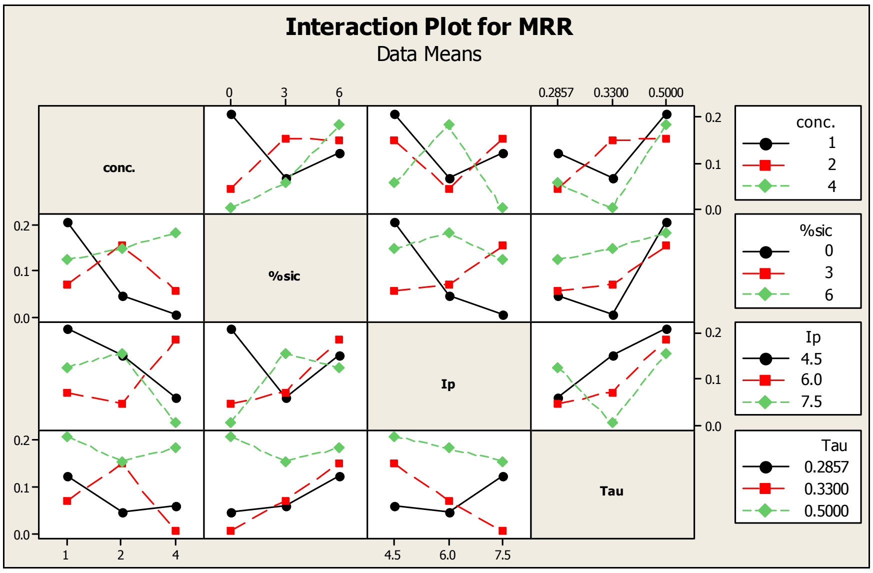
From the main effects plot (Figure 2), it can be observed that the MRR of the machined metal matrix composite (MMC) surface increases when concentration of powder is low, % Sic in MMC is increased; peak current (I_p) is low and duty cycle is increased. The analysis of the experimental results using the main effect plot gave the following optimum machining condition that result in maximum MRR = 0.276515 g/min at conc. = 1 g/l, %SiC = 0%, I_p = 4.5 A and τ = 0.5 (Figure 2).

Figure 2 Main effect plot for MRR for different process parameters (see online version for colours)



The interaction plot of MRR is shown in the figure below, where each plot exhibits the interaction between four different machining parameters like conc., %SiC, I_p and Tau. This implies that the effect of one factor is dependent upon another factor.

Figure 3 Interaction plot for MRR (see online version for colours)



The interaction plot of MRR is shown in the above figure, where each plot exhibits the interaction between four different machining parameters like conc., %SiC, I_p and Tau. This implies that the effect of one factor is dependent upon another factor.

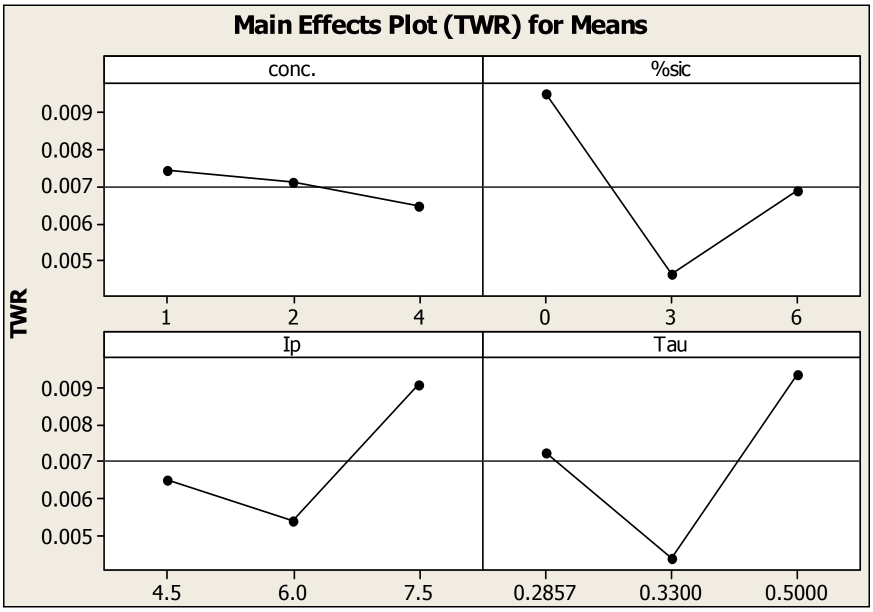
4.2 Taguchi analysis: TWR versus conc., %SiC, I_p, τ

Similarly ranking of predominant parameters influencing the TWR using mean values obtained for different parameter levels are listed in Table 4. It can be observed from these tables that duty cycle was the most dominant parameter influencing the TWR. The main effect plot for TWR is shown in Figure 4.

Table 4 Response for TWR

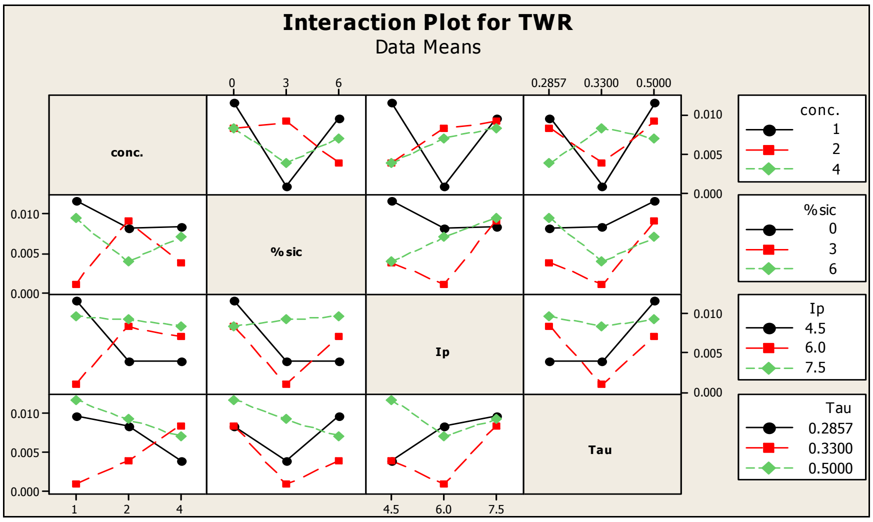
Level	*Conc.*	*%SiC*	I_p	*T*
1	0.007444	0.009493	0.006501	0.007256
2	0.007111	0.004634	0.005408	0.004381
3	0.006446	0.006875	0.009093	0.009364
Delta	0.000998	0.004859	0.003684	0.004983
Rank	4	2	3	1

Figure 4 Main effect plot for TWR for different process parameters (see online version for colours)



From this above plot TWR was found to be minimum when there will be an increase in concentration of the powder, %SiC is at medium level, i.e., 3%, peak current at 6A and duty cycle at 0.33. The analysis of the experimental results using the main effect plot gave the following optimum machining condition that result in minimum TWR = 0.0001315 g/min at conc. = 4 g/l, %SiC = 3%, I_p = 6 A and τ = 0.33 (Figure 4).

Figure 5 Interaction plot for TWR (see online version for colours)



The interaction plot of TWR is shown in the above figure where each plot exhibits the interaction between four different machining parameters like conc., %SiC, I_p and Tau. This implies that the effect of one factor is dependent upon another factor.

4.3 Taguchi analysis: Ra versus conc., %SiC, I_p, Tau

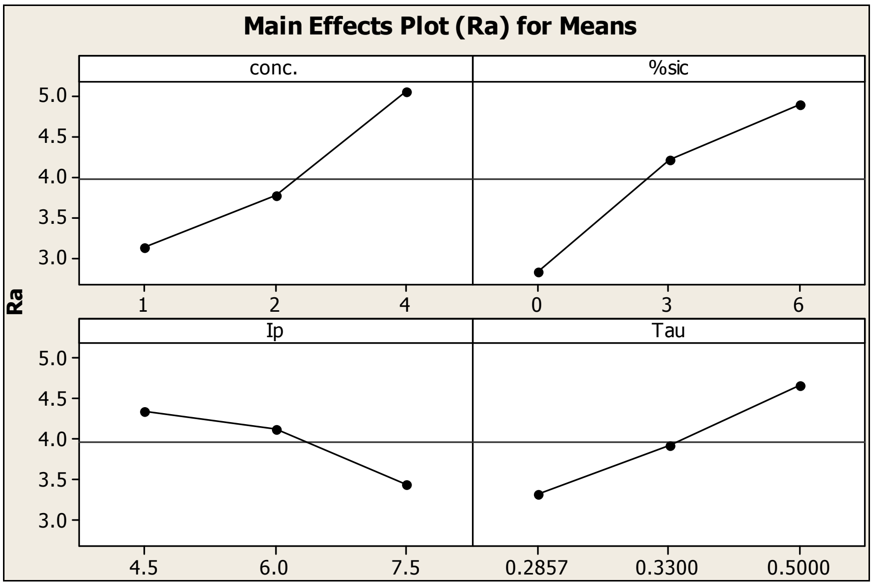
Similarly ranking of predominant parameters influencing the SR using mean values obtained for different parameter levels are listed in Table 5. It can be observed from these tables that %SiC in the work piece was the most dominant parameter influencing the SR. The main effect plot for SR is shown in Figure 6.

Table 5 Response table for Ra

Level	*Conc.*	*%SiC*	I_p	*T*
1	3.117	2.813	4.356	3.316
2	3.76	4.212	4.134	3.93
3	5.046	4.898	3.433	4.678
Delta	1.93	2.085	0.922	1.362
Rank	2	1	4	3

From the above figure, Ra was found to be minimum when the concentration of the powder is minimum at 1 g/l, %SiC is at low level, i.e., 0%, peak current at high level and duty cycle at 0.2857. The analysis of the experimental results using the main effect plot gave the following optimum machining condition that result in minimum Ra = 0.755437 µmat conc. = 1 g/l, %SiC = 0%, I_p =7.5 A and τ =0.2857 (Figure 6).

Figure 6 Main effect plot for SR for different process parameters (see online version for colours)



4.4 Grey analysis

In grey relational analysis (GRA), black represents having no information and white represents having all information. A grey system has a level of information between black and white. This analysis can be used to represent the grade of correlation between two sequences so that the distance of two factors can be measured discretely. In the case when experiments are ambiguous or when the experimental method cannot be carried out exactly, grey analysis helps to compensate for the shortcoming in statistical regression. GRA is an effective means of analysing the relationship between sequences with less data and can analyse many factors that can overcome the disadvantages of statistical method.

The grey relation algorithm involves the following steps:

Step 1 Normalise the experiment result of each performance characteristic.

Step 2 Compute the value of $0_i(k) = \| x_0^*(k) - x_i^*(k) \|$, $\min(k) = \max \forall j \mathcal{E}_i \min \forall k \left\| x_0^*(k) - x_j^*(k) \right\|, \max(k) = \max \forall j \mathcal{E}_i \max \forall k \left\| x_0^*(k) - x_j^*(k) \right\|$ to calculate the grey relational coefficient.

Step 3 Calculate the grey relational grade by the mean value of grey relational coefficient.

Step 4 Compute the response table and response graph for each level of the EDM parameters.

Step 5 Recognise the noticeable variable factors and selects the optimal levels of EDM parameters.

Step 6 Run confirmation test and verify.

4.4.1 Data pre-processing

In GRA, when the range of sequences is large or standard value is large, the functions of factors are neglected. However, if a factor's measured unit, goals, and directions are different, the GRA might produce incorrect results. Therefore, original experimental data must be pre-processed to avoid such effects. Data pre-processing is the process of transforming the original sequence to a comparable sequence. For this purpose, the experimental results are normalised in the range of zero and one, the process is called grey relational generating. Three different types of data normalisation according to whether we require the lower is better, the higher is better or nominal the best. The normalisation is taken by three approaches. If the target value of original sequence is infinite, then it has a characteristic of 'the larger the better' (e.g., benefit). The original sequence can be normalised as follows:

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{8}$$

where $x_i^0(k)$ is the original sequence, $x_i^*(k)$ the sequence after the data pre-processing, $\max x_i^0(k)$ the largest value of $x_i^0(k)$ and $\min x_i^0(k)$ implies the smallest value of $x_i^0(k)$ .When the form 'the-smaller-the-better' becomes the expected value of the data sequence, the original sequence can be normalised as:

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{9}$$

However, when the demanded value becomes the expected value in the analysis, the original sequence can be normalised as following to achieve the destination as close as possible:

$$x_i^*(k) = 1 - \frac{\left| x_i^0(k) - x^0 \right|}{\max\left\{ \max x_i^0(k) - x^0 : x^0 - \min x_i^0(k) \right\}} \tag{10}$$

where x^0 implies the destination of the assigned value in the data sequence.

Table 6 The sequences of each performance characteristics after data pre-processing

Exp. no	*MRR*	*TWR*	*Ra*
Reference sequence	1	1	1
1	1	0	0.801394464
2	0.325915502	1	0.710542996
3	0.588005745	0.195119497	0.843650961
4	0.205992292	0.323168668	1
5	0.736618649	0.237805603	0.564758082
6	0.711154309	0.72560892	0.383055145
7	0	0.309952164	0.746606803
8	0.261703393	0.728462587	0.385899007
9	0.871754699	0.430611069	0

4.4.2 Grey relation coefficient and grey relational grade calculation

The grey relational coefficient is defined as:

$$\gamma\left(x_i^0, x_{i\omega_i}^*\right) = \Gamma_i = \frac{\Delta \min + \zeta. \Delta \max}{\Delta_{0i}^* + \zeta. \Delta \max} \tag{11}$$

The grade $\gamma\left(x_i^*, x_{i\omega_i}^*\right), \Gamma_i$ implies the correlation between the reference sequence and the specific sequence x_i to be compared to $.\zeta$ is distinguish or identification coefficient: $\in (0,1), \zeta = 0.5$ is generally used.

$$\Delta_{0i}^* = \frac{1}{n} \sum_{k=1}^{n} \Delta_{0i}(k) \tag{12}$$

$$0 < \gamma\left(x_i^*, x_{i\omega_i}^*\right) \leq 1 \tag{13}$$

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

$$\Delta_{0i}(k) = \left|x_0^*(k) - x_{i\omega_i}^*(k)\right| \tag{14}$$

$$\Delta \max = \max \max \left|x_0^*(k) - x_{j\omega_j}^*(k)\right| \tag{15}$$

$$\Delta \min = \min \min \left|x_0^*(k) - x_{j\omega_j}^*(k)\right| \tag{16}$$

After obtaining the grey relational coefficient, the average of the grey relational coefficient is normally taken as the grey relational grade. The grey relational grade is defined as follows:

$$r_i = \frac{1}{m} \sum_{k=1}^{n} \gamma(k) \tag{17}$$

However, since in real application the effect of each factor on the system is not exactly same. Equation (17) can be modified as;

$$ri = \frac{1}{m} \sum_{k=1}^{n} \omega(k)\gamma(k) \quad , \sum_{k-1}^{n} \omega_k = 1 \tag{18}$$

where ω_k represents the normalised weighing value of factor k. Given the same weights.

In the GRA, the grey relational grade is used to show the relationship among the sequences. If the two sequences are identical, then the value of grey relational grade is equal to 1. The grey relational grade also indicates the degree of influence that the comparability sequence could exert over the reference sequence. Therefore, if a particular comparability sequence is more important than the other comparability sequences to the reference sequence, then the grey relational grade for that comparability sequence and reference sequence will be higher than other grey relational grades.

The deviation sequences; Δ_{0i}, $\Delta_{max}(k)$ and $\Delta_{min}(k)$ for i = 1,2……9, k = 1 – 3 can be calculated as follows:

$$\Delta_{01}(1) = \left|x_o^*(1) - x_1^*(1)\right| = 1 - 1 = 0$$

$$\Delta_{01}(2) = \left|x_o^*(2) - x_1^*(2)\right| = 1 - 2 = 1$$

$$\Delta_{01}(3) = \left|x_o^*(3) - x_1^*(3)\right| = 1 - 0.801394464 = 0.198605536$$

The results for all deviation sequence are given in Table 7.

Table 7 The deviation sequences

Exp. no.	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$	$\Delta_{0i}(3)$
1	0	1	0.198605536
2	0.674084498	0	0.289457004
3	0.411994255	0.804880503	0.156349039
4	0.794007708	0.676831332	0
5	0.263381351	0.762194397	0.435241918
6	0.288845691	0.27439108	0.616944855
7	1	0.690047836	0.253393197
8	0.738296607	0.271537413	0.614100993
9	0.128245301	0.569388931	1

Using Table 7, the following can be calculated.

$$\Delta_{\max} = 1 \quad \Delta_{\min} = 0$$

Table 8 lists the grey relational coefficient and grade for each experiment of the L_9 OA.

Table 8 Grey relational coefficient and grey relational grade

Exp. no.	*Grey relational coefficient*			*Grey relational grade*
	MRR	*TWR*	*Ra*	
1	1	0.333333333	0.715711477	0.714713443
2	0.425863727	1	0.633346715	0.660349505
3	0.548249067	0.38317685	0.761789796	0.562789621
4	0.386396462	0.424869721	1	0.582019501
5	0.654980632	0.396135493	0.534621032	0.541219211
6	0.633837525	0.645668594	0.447649674	0.58153049
7	0.333333333	0.420151178	0.663664076	0.45847791
8	0.403780481	0.648056713	0.448792347	0.490566911
9	0.795867473	0.467556738	0.333333333	0.55861401

It is clearly observed from Table 8 that the EDM process parameters setting of experiment no. 1 has the highest grey relation grade. Thus, the first experiment gives the best multi-performance characteristics among the nine experiments.

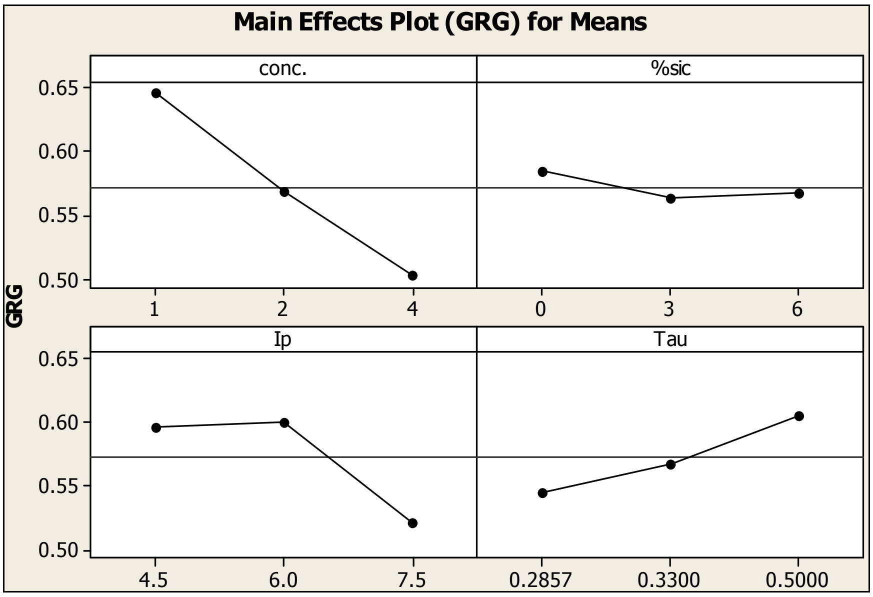
Using the software Minitab the response table for MRR is generated in Table 9.

Table 9 Response table for GRG

Level	*Conc.*	*%sic*	*Ip*	*Tau*
1	0.646	0.5851	0.5956	0.5451
2	0.5683	0.564	0.6003	0.5668
3	0.5026	0.5676	0.5208	0.6048
Delta	0.1434	0.021	0.0795	0.0597
Rank	1	4	2	3

Ranking of predominant parameters influencing the GRG using mean values obtained for different parameter levels are listed in Table 9. It can be observed from these tables that powder concentration in dielectric was the most dominant parameter influencing the GRG. The main effect plot for GRG is shown in Figure 7.

Figure 7 Main effect plot for GRG for different process parameters (see online version for colours)



From Figure 7, GRG was found to be maximum when the concentration of the powder is minimum at 1 g/l, %SiC is at low level, i.e., 0%, peak current at 6 A and duty cycle at 0.5. The analysis of the experimental results using the main effect plot gave the following optimum machining condition that result in maximum MRR = 0.1707 g/min, minimum TWR = 0.0107 g/min and minimum Ra = 2.8188 µm (Figure 7).

4.4.3 Analysis of variance (ANOVA)

The ANOVA investigates which PMEDM process parameters significantly affect the performance measures. This is revealed by separating the total variability of the GRGs, which is measured by the sum of squared deviations from the total mean of the GRG into contributions by each process parameter and error.

Table 10 ANOVA for GRG

Source	*Sum of squares*	*Df*	*Mean square*	*% contribution*
Model	0.049093423	8	0.006136678	
A	0.030916376	2	0.015458188	62.9745772
B	0.00075866	2	0.00037933	1.54533874
C	0.011933614	2	0.005966807	24.3079697
D	0.005484773	2	0.002742387	11.1721143
Pure error	0	0		0
Cor. total	0.049093423	8		100

The results of ANOVA (Table 10) indicate that powder concentration and peak current are the most significant process parameters affecting the multiple performance measures. The other factor having significant effects is the duty cycle. The increase in the abrasive powder concentration also helps to bridge the gap between the tool electrode and the work material, thus increasing the rate of MRR. This may be attributed to the fact that the bridging effect (formation of powder chain under discharging area) generates multiple discharging effects within a single input pulse, thus increasing frequency of discharging. Thus, the bridging effect between both the electrodes facilitates the dispersion of discharge into several increments and subsequently increasing MRR. The faster discharging within a single input pulse causes faster erosion of material. Moreover, it is found that higher abrasive particle concentration with higher particle size display a discharge interference phenomenon. Furthermore, it has also been observed that at higher abrasive powder concentration results in inter-electrode gap contamination due to the debris and disturbs the discharging between the tool electrode and the work material, eventually leading to abnormal discharges and frequent sorting of the two electrodes and subsequently low MRR and poor surface finish. Thus, in this study, the highest metal removal depths were achieved at the optimal concentration of Al_2O_3(1 g/L).

4.4.4 Surface plot for GRG

Figure 8 Surface plot for GRG vsconc., %SiC (see online version for colours)

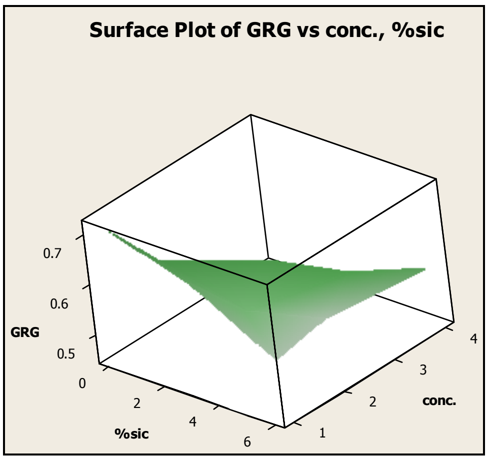
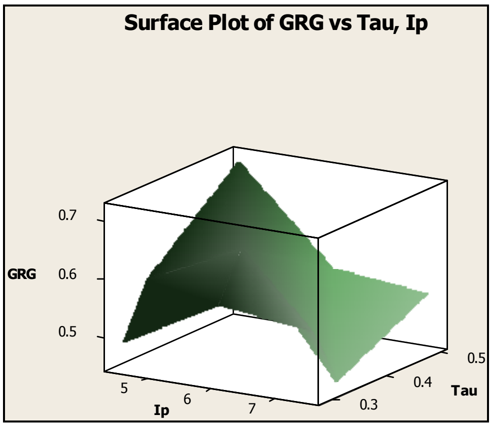


Figure 9 Surface plot for GRG vstau, I_p (see online version for colours)



4.4.5 Confirmation tests

Once the optimal level of the process parameters is identified, the final step is to predict and validate the improvement of the performance measures using the optimal level. A good indication of the satisfactory experimental runs is observed by subsequently comparing the results of the confirmation tests with the predicted value. The purpose of the confirmation experiment is to verify the conclusions drawn during the analysis phase.

The optimal combination of parameters $A_1B_1C_2D_1$ obtained by grey relational and Taguchi analysis is not present in above L_9 OA used for purpose. Hence a new work piece was allowed to be machined for the set of experiment using optimal parameter values. The respective output parameters obtained are tabulated in Table 11.

Table 11 Comparison of experimental and predicted values

	Optimal machining parameters	
Combination level	$A_1B_1C_2D_1$	$A_1B_1C_2D_1$
MRR, g/min	0.1707 g/min	0.1810
TWR, g/min	0.0107 g/min	0.0105
SR, Ra, lm	2.8188 µm	2.7560

- Experiment is done by taking four parameters having three level each to calculate the three performance parameter powder concentration in dielectric, material composition (Si-C) percentage, pulse current and duty cycle and performance parameter MRR,TWR,SR.
- In Taguchi analysis, higher MRR is calculated at concentration 1 gm/litre, % of Si-C 0%,pulse current 4.5 A and duty cycle 0.5, Min TWR at concentration 4 gm/litre, %Si-cC is 3%,and pulse current 6 amper and duty cycle 0.33 .Min Sr in concentration at 1 gm/litre, %Si-C 0%, pulse current 7.5 amper and duty cycle 0.28.
- In grey analysis all the performance parameter are showing optimised result at concentration 1 gm/litre, % of Si-C 0%, pulse current 6 amper, duty cycle .5.

4.4.6 Conclusions

In this study, the GRA approach, based on the orthogonal experimental design table, is applied to find the optimal machining parameters which minimise the required multiple performance characteristics for PMEDM of MMC. The L_9 OA is selected as experimental plan for the four control factors namely; powder concentration, % Sic in MMC, pulse current (I_p) and duty cycle (τ). The MRR, TWR, and SR (Ra) are adopted to evaluate the machinability performance characteristics. A confirmation test within the optimal machining parameters is conducted to indicate the effectiveness of this proposed approach. The conclusions of study may be summed up as follows: The average GRG was obtained through the GRC of each performance characteristic. The largest value of GRG for the PMEDM parameters was found. On this basis, it is stated that the powder concentration has the strongest effect among the other process parameters used to study the multiple performance characteristics. The order of importance of the process parameters to the multiple performance characteristics is powder concentration, peak current (I_p), duty cycle (τ) and %SiC of MMC. The optimal level setting of four process parameters are A1, B1, C2, D1 for maximising MRR and minimising tool wear and SR (Ra) according to the results of response table and main effects plot. Based on the optimal levels of machining parameters, the confirmation tests yields an increase of MRR from 0.1707 g/min to 0.1810 g/min where as the TWR and the SR (Rmax) is reduced 0.0107 g/min 0.0105 g/min and 2.8188 µm to 2.75601 m respectively. It can be inferred that the present experiment have shown clearly that the MRR, TWR and SR in the PMEDM process can be improved effectively through this proposed approach. This study also indicates that GRA approach could be applied successfully to other operations in which performance measures are determined by many process parameters at multiple quality requests. In this paper, thermal distersion of heat affected zone in microscopic level, also recast layer thickness on the work piece material has not taken into account for which the multi-performance characteristic may give different optimised combination. The biological effect is also not considered.

The present work provides a lot of insight into the optimisation of machining parameters in PMEDM still further work, as given below can be carried out. The parameter optimisation may be carried out by experimenting on other composite material having different composition. Optimisation can be carried out with more numbers of parameters. Other evolutionary and bio-inspired computing techniques can be applied for parameter optimisation and the results can be compared with the results of the present work.

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