Modeling and parametric optimization of electrical discharge machining on casted composite using central composite design

Article *in* International Journal on Interactive Design and Manufacturing (IJIDeM) · May 2023

DOI: 10.1007/s12008-023-01323-7

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International Journal on Interactive Design and Manufacturing (IJIDeM)
https://doi.org/10.1007/s12008-023-01323-7

ORIGINAL PAPER

Modeling and parametric optimization of electrical discharge machining on casted composite using central composite design

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Received: 8 February 2023 / Accepted: 31 March 2023

Abstract
MMCs are broadly used in several industrial applications because of their excellent mechanical properties. Hard materials and composites cannot be machined by typical conventional methods. so nonconventional machining methods such as Electrical discharge machining are mostly used. This work focuses to optimize the process variables of EDM of Al5456/SiC/Flyash hybrid composites. The impact of three most significant variables including pulse-off time, current and pulse-on time are examined. Central Composite Design (CCD) based RSM is applied for experimentation. The development model for material removal rate (MRR) and surface roughness (SR) are investigated by using CCD technique. ANOVA is implemented to identify the most significant variables and their output response of MRR and SR. From the validation result, the maximum values of MRR and SR are identified as 0.783 mm^3/min and 13.26 µm, whereas minimum values are 0.249 mm^3/min and 8.24 µm. ANOVA results show that current and pulse OFF time are highly significant variables to increase MRR and SR. The development of a regression model and 3D/Contour are made to predict and evaluate the Material Removal Surface and Surface roughness.

Keywords MRR · ANOVA · EDM process · CCD technique · MMC

1 Introduction

Ceramic particle-reinforced MMCs exhibit superior mechanical and wear properties compared to base metals. MMCs illustrate the synergistic advantages of the matrix and reinforcements. [1]. Aluminum-based MMCs represent the best solution among the MMCs, Due to its inherent characteristics including light weight, excellent strength, stiffness, superior thermal conductivity and good corrosion resistance [2, 3]. Different fabrication procedures are used to prepare the MMCs. Among them, the liquid-state technique is the more practical and affordable approach. Stirring speed is the main element that influences how composites behave during liquid-state processing, although stirring duration also has an impact on the amount of reinforcement added to the matrix [4]. The most crucial stage of manufacturing is machining. The components are made by casting, but before they are suitable for use in real-time applications. Due to their extremely abrasive characteristics, MMCs are challenging for conventional machining [5]. Because of their high power requirements, surface profiles, severe cutting tool wear, and increased laboriousness in creating complex shapes, MMCs make traditional machining problematic [6]. Producing intricate designs that would be impossible to make using traditional cutting equipment. Therefore, as it is employed to manufacture complicated and sophisticated components for the aerospace and automotive industries, Electrical Discharge Machining (EDM) is best for processing AMCs. To

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Published online: 02 May 2023

process copper beryllium alloys, Guha et al. [7] performed several studies using various electrodes utilized in EDM and the copper electrode with positive polarity had the highest MRR, whereas the graphite electrode with negative polarity had the highest MRR. For application in biodegradable implants, M Somasundaram et al. cut AZ31 magnesium alloy into complicated structures. Process parameter optimization is tried by fusing Taguchi and multi-attribute optimization techniques. In this study, multi-response optimization is carried out via MCDM techniques, such as GRA and TOPSIS. The effects of the input variables are examined through ANOVA and contour plots. According to the analysis's findings, the Pulse-ON time, with contribution rates of 40.63% and 62.49%, respectively, is the process parameter that most significantly affects GRA and TOPSIS [8]. During Al/B4C machining, the impact of the EDM parameters [current, pulse-on time, off time, and electrode material] on the MRR, wear rate, and SR is examined [9]. To successfully implement Taguchi's OA technique for parametric optimization, Tribeni Roy et al. selected the four parameters of the combined fuzzy AHP and TOPSIS approaches in the design of the multi-response experiment [10]. To optimize the parameters for 6061Al-Al2O3p-20P, Shankar Singh used DOE and GRA method. He also introduced tool electrode lift time as one of the factors to be taken into account in EDM [11]. S/N ratio was estimated for optimization and the ideal solution (TOPSIS) was employed to optimise the responses of MRR and SR for Al–Cu/TiB2 composites during machining [12]. Nayak BB et al. used the AHP and TOPSIS to combine many outputs into a single response. multi-response optimization procedure was used to create the best process parameters in the WEDM process [13].Fuzzy TOPSIS technique has been employed to optimize responses including MRR, SR and tool wear rate. ANOVA revealed that the most prominent parameter is relevant for many surface integrity-based performance characteristics. [14]. An effort is made to mill AZ31 alloy through EDM to improve input parameters by merging multi-response and Taguchi optimization techniques such as TOPSIS and GRA. ANOVA and contour plots are used to assess the impact of process factors. According to the observations, the Pulse-ON time is the most substantially impacting process parameter in both GRA and TOPSIS, with contributions of nearly 41% and 63% respectively [15]. Siva Bhaskar et al. investigated the abilities of several Hybrid MCDM approaches built on TOPSIS, ELECTRE ,MOORA, VIKOR & PROMETHEE in combination with AHP. All five techniques used AHP weights as input to determine the ranking of supplied options. the case study example was provided to demonstrate how to prioritize polymer biomaterials utilized in dentistry applications based on several parameters [16]. The literature studies are the chief role to assist us to realize the choosing suitable variables of EDM and optimization techniques. The above literature reviews revealed that only a small number of studies addressed the impact of the input parameters of pulse time in ON and OFF conditions, dielectric medium, voltage, current, and electrode material on the response of MRR and SR. The novelty of this work is to prepare the Al5456/SiC/Flyash composites through Stir casting method and RSM-Composite Central Design [17] is implemented to evaluate the best optimal parameter to improve the output responses (MRR & SR). Generally, SR and MRR responses are depending on suitable input variables. We have selected three factors pulse time ON, pulse time OFF and current. The CCD is used to guide the execution of 20 experiments, and the results of these experiments show increased wear rate and significant relationships between certain variables. Al5456/SiC/Flyash hybrid composites are prepared for a variety of uses, such as the construction of pressure vessels, truck and vehicle bodies, mine skips etc. Our objective is to find the wear rate performance for the prepared composite material and also evaluate the most influencing parameter that affects the wear rate with the support of design expert software.

2 Materials and methods

The chemical weight% for Al5456 is presented in Table 1. Typically, samples are prepared using the stir-cast method in a heated furnace. First, we must pre-hate both the silicon carbide (5%) and fly-ash (3%) powders for 15 to 25 min at a certain temperature of about 300 °C. Al 5456 material was placed into the furnace to be heated for 40 to 45 min at a temperature of 700 to 850 °C before being added to the heated powder. Add reinforcing elements to the furnace after the melting of the Al alloy. All elements are mixed using stainless steel as a stirrer, and then molten metal (Al5456/Flysh/Sic) is poured into a permanent mold to obtain a sample for EDM process.

Electrical Discharge Machining is comparable to laser cutting as well as other related technologies [18]. Without using any mechanical force, the surplus material is eliminated. Because of this reason, many people consider it to be a non-traditional manufacturing approach [19–23]. This process is beneficial for molding and tooling in a range of industries. Al matrix composite is machined using an EDM machine, and Fig. 1 depicts the machine's schematic diagram. Al5456/Flysh/Sic, a work material with an average particle size of 5 m, is used in dielectric machining. A cylindrical Cu tool with a 20 mm external diameter and a 50 mm length is chosen as the electrode because it performs best in terms of toughness, melting point, cost, and quality when compared to other non-ferrous metals, kerosene oil served as a dielectric. A milling machine is used to prepare a sample of the material with a dimension of 250 × 400 × 15 mm^3. The chosen variables for this study included pulse-on time

Table 1 Al5456 alloy chemical compositions

Elements	Cr	Cu	Fe	Mg	Si	Mn	Ti	Zn	Al
%	0.22	0.12	0.42	5.3	0.25	1.1	0.5	0.45	Remain

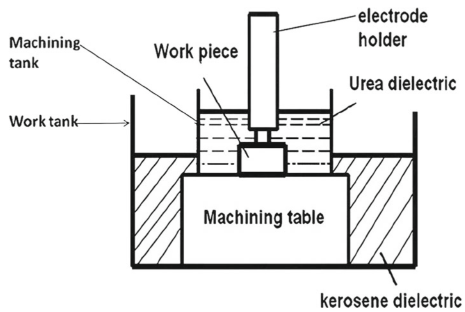

Fig. 1 EDM setup

Table 2 Process variables of EDM

Variables	Name	Levels		
		Minimum	Center	Maximum
A	Pulse ON time	30	40	50
B	Pulse OFF time	8	10	12
C	Current	10	12	14

(A), pulse-off time (B), and current (C), as it is previously mentioned [24]. Process variables of EDM such as current, pulse on time and pulse off time could be noticeable in the machining performance of Al 5456 composite. Each factor is represented by three different values, which are marked as −1, 0 and + 1, to indicate the minimum, middle, and maximum levels. The sort of variables (A,B &C) are chosen as 30 to 50 µs, 8 to 12 µs and 10 to 14 A. Ranges and levels of each variable (A, B and C) are considered according to trial runs in Table 2.

The Experimental tests are planned by using RSM-CCD approach. Using Design Expert − 13, Twenty parameter combinations are designed which have the non-center points 14 and 6 center points per block. The process variables levels and measured responses are specified in the design matrix in Table 3. MRR and SR are the responses taken into consideration in this research for the assessment of machining performance. MRR can be determined using the formula below.

$$MRR = \frac{(W1 - W2)}{(\rho t)}$$

Table 3 Experimental CCD result

Std	Run	A	B	C	MRR (mm^3/min)	SR (µm)
13	1	40	10	10	0.453	8.59
18	2	40	10	12	0.472	9.26
2	3	50	8	10	0.256	11.28
10	4	50	10	12	0.523	10.86
19	5	40	10	12	0.489	8.24
7	6	30	12	14	0.628	9.15
1	7	30	8	10	0.249	12.48
5	8	30	8	14	0.782	11.28
20	9	40	10	12	0.623	7.89
17	10	40	10	12	0.552	8.57
3	11	30	12	10	0.359	10.25
6	12	50	8	14	0.387	13.26
9	13	30	10	12	0.659	8.57
8	14	50	12	14	0.479	10.89
16	15	40	10	12	0.279	11.25
15	16	40	10	12	0.387	12.78
14	17	40	10	14	0.654	8.56
12	18	40	12	12	0.783	9.47
4	19	50	12	10	0.548	8.43
11	20	40	8	12	0.713	11.88

where, W1 = Initial weight, W2 = Final weight, ρ = Density, t = Machine time(15 min).

Surface meter is used for calculating SR value. The readings of SR are measured three times at various places of the composite material and average the values.

3 Results and discussion

Experimental tests were analyzed with help of ANOVA [17] by accessing chosen variables (A,B, and C) for the MRR and SR [25]. The overall results for MRR and SR are exposed in Figs. 2 and 3 respectively. Variables have identified the maximum and least optimal combination parameters for MRR are A2-B3-C2 (40 µs, 12 µs & 12 Amp) and A1-B1-C1 (30 µs, 8 µs & 10 Amp) respectively and the values of MRR are 0.783 mm^3/min & 0.249 mm^3/min. Similarly maximum and minimum for SR are attained by Variables A3-B1-C3 (50 µs, 8 µs & 14 Amp) and A2-B2-C2 (40 µs, 1 µs & 12 Amp) and the SR values are 13.26 µm and 8.24 µm respectively

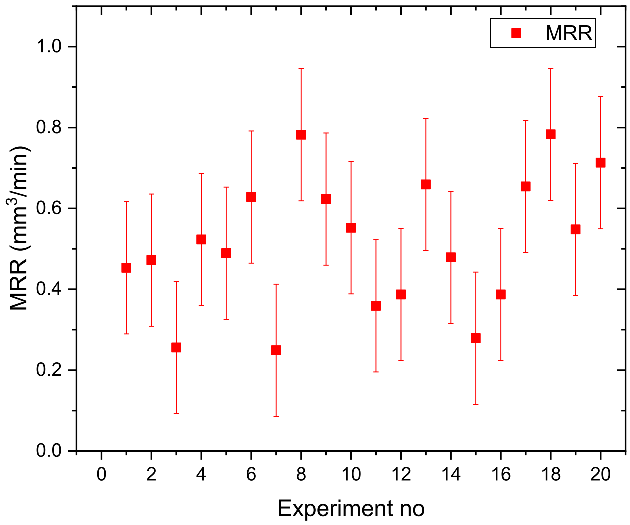

Fig. 2 MRR experimental results

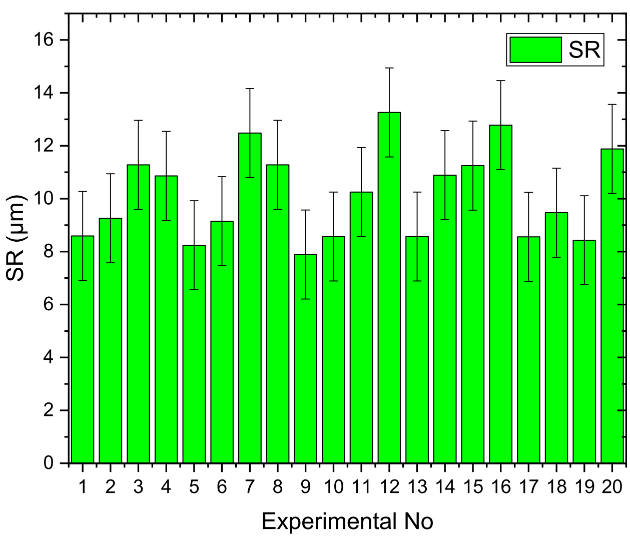

Fig. 3 SR experimental results

and it is identified that standard deviation of MRR and SR are 0.16345 and 1.682.

The comprehensive results are provided including regression model, ANOVA result, 3D and contour plots for interaction variables and optimization of parameters for output responses.

3.1 ANOVA

Design expert 13 Version is working as statistical software that generates mathematical models of reactions [26–30]. ANOVA is accompanied to estimating the impact of pulse on time, current and pulse off time. Tables 4 and 5 illustrate the outcomes of ANOVA of MRR and SR. The analysis is done at a significance level (5%) & confidence level (95%) [31–34]. Husain Mehdi et al. developed the empirical analysis to forecast responses of friction stir processing with alumina particle at 95% confidence level [35]. The quadratic model is the right design for clarifying MRR and SR outcomes among the other polynomials test which shows the least p value. The empirical models developed for MRR and SR are evaluated by the F and *P* tests. Form Table 4, It is established that model F-ratio of 4.96 and *P* value of 0.0440 are attained for material removal rate. The model is reliable because *P* value is less than 0.05. However, lack of fit is 1.49, the most significant factor on MRR is current which value is less than 0.05. In the case of SR, It was found from Table 5 that the model F-ratio of 7.68 and *p* value of 0.02141 are attained for surface roughness. This model is also significant because *P* is less than 0.05 [36–38]. Pulse OFF time is the most important factor which improves surface roughness values because *P* value is 0.0268. Variable C and B are the supreme important factors for increasing the value of MRR and SR respectively. Variables A & B are insignificant parameters on MRR whereas variables A & C are insignificant parameters on SR.

3.2 Regression model

A predictive modeling technique called regression analysis examines the connection between the targeted variables MRR & SR and the independent variables A,B &C in a dataset [39–42].

Equations (1) & (2) are used to present a regression model to predict MRR and SR for the specified parameters [43].

$$\begin{aligned}\text{MRR} = &-4.80804 + 0.069437A - 0.412955B \\ &+ 0.949705C + 0.002675A * B \\ &- 0.014500A * C - 0.000569B * C - 0.000569\,A^2 \\ &+ 0.025023B^2 - 0.023602C^2\end{aligned} \tag{1}$$

$$\begin{aligned}\text{SR} = &+54.86227 - 0.823305A - 7.91109B + 2.06834C \\ &- 0.005375A * B \\ &+ 0.042125AC + 0.018125BC + 0.005018A^2 \\ &+ 0.365455\,B^2 - 0.159545C^2\end{aligned} \tag{2}$$

3.3 3D/contour plots

3.3.1 Material removal rate

This section interprets the impact of variables (A, B & C) on output responses of MRR & SR.3D /contour graphs explain the interaction between the two variables simultaneously. The effect of process variables (A,B &C) on MRR are presented in the form of plots in Figs. 4, 5 and 6. The 3D/contour plot of pulse-on time vs. pulse off time is revealed in Fig. 4.

Table 4 ANOVA for MRR

Source	SS	DF	MS	F	P
Model	0.3241	9	0.0360	4.96	0.0440
A:Pulse ON time	0.0234	1	0.0234	1.28	0.2849
B: Pulse OFF time	0.0168	1	0.0168	0.9162	0.3610
C: Current	0.1134	1	0.1134	6.18	0.0322
A*B	0.0229	1	0.0229	1.25	0.2900
A*C	0.0685	1	0.0685	3.73	0.0822
B*C	0.0269	1	0.0269	1.47	0.2537
A*A	0.0089	1	0.0089	0.4854	0.5018
B*B	0.0276	1	0.0276	1.50	0.2485
C*C	0.0245	1	0.0245	1.34	0.2746
Residual	0.1835	10	0.0183		
Lack of Fit	0.1097	5	0.0219	1.49	0.3373
Error	0.0738	5	0.0148		
Total	0.5076	19			

Table 5 ANOVA for SR

Source	SS	DF	MS	F	P
Model	32.39	9	3.60	7.68	0.02141
A:Pulse ON time	0.8940	1	0.8940	0.4184	0.5323
B: Pulse OFF time	14.38	1	14.38	6.73	0.0268
C: Current	0.4452	1	0.4452	0.2083	0.0657
A*B	0.0925	1	0.0925	0.0433	0.0839
A*C	5.68	1	5.68	2.66	0.1341
B*C	0.0421	1	0.0421	0.0197	0.0891
A*A	0.6925	1	0.6925	0.3241	0.0817
B*B	5.88	1	5.88	2.75	0.1282
C*C	1.12	1	1.12	0.5241	0.4857
Residual	21.37	10	2.14		
Lack of Fit	2.61	5	0.5218	0.1391	0.9753
Error	18.76	5	3.75		
Total	53.76	19			

It is noticed that MRR values is increased with an increase of pulse OFF time and a decrease of pulse ON time which means the MRR is proportional to variable B ,indirectly to Variable A. due to variation of pulse time OFF, Space is decreased between electrode and composite materials so more energy is transferred between them which leads to increasing MRR. Figure 5 shows the plot between Pulse ON time and Current.it is witness when there is an increment of current value, MRR is increased whereas MRR is reduced when the pulse OFF duration increases due to a drop in dielectric flushing pressure and a decrease in heat loading at both electrodes, resulting in a lower MRR value [44]. Temperature is produced high due to the increment of current value so the value of MRR also increased Fig. 6 shows 3D and contour plots for Pulse OFF time and current. It is also noticed that MRR increased significantly due to the increasing of current and a decrease in Pulse OFF time. From these above plots, we found that current is most important variable to improve MRR of prepared composites [45]. The discharge gap is stimulated every time and more material removal occurs. Because the addition of SiC and flyash, as well as the current factor, reduces the gap distance between the workpiece and the electrode, a lot of energy is delivered in the gap, resulting in fast material removal. MRR increased when discharge current and reinforcing powders were increased.

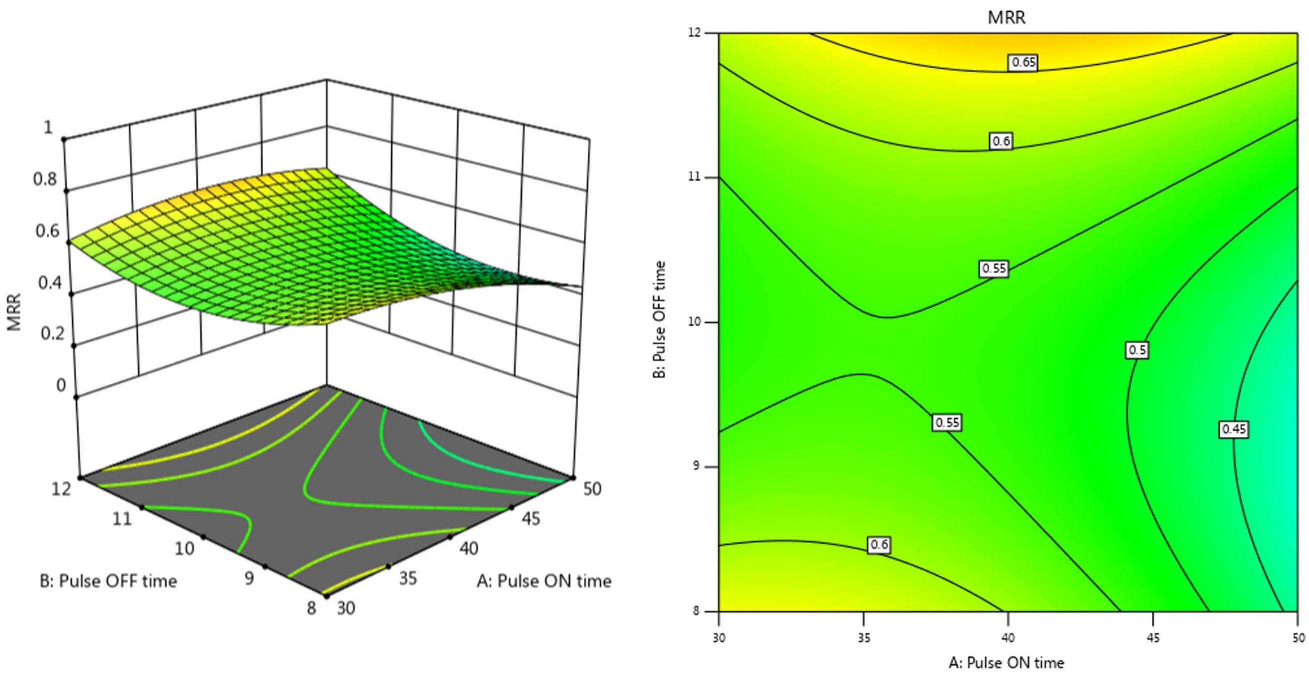

Fig. 4 Pulse ON time vs. pulse OFF time on MRR

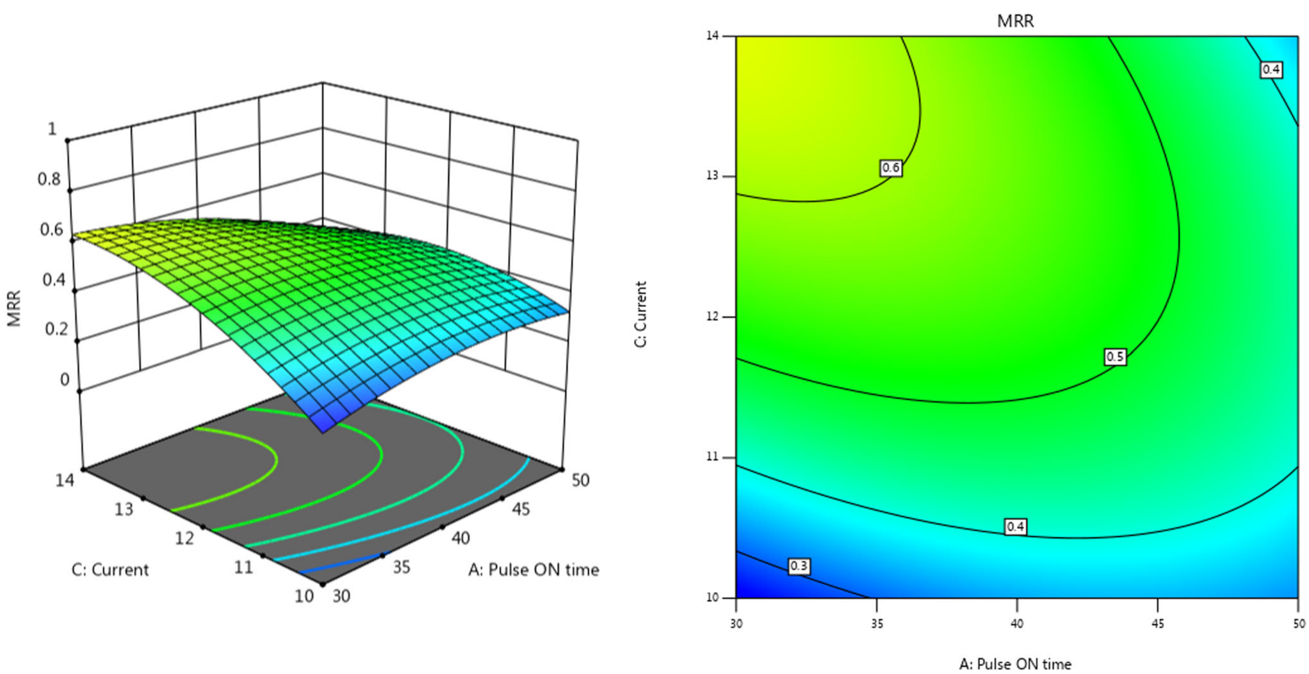

Fig. 5 Pulse ON time vs. Current on MRR

3.3.2 Surface roughness

The 3D and contour plot of ON time vs. OFF time for SR is presented in Fig. 7. It is noticed that SR values are increased with the rise of pulse OFF time and pulse ON time which mean the SR is directly proportional to variable A &B. due to variation of pulse time OFF and pulse ON time, Space is decreased between an electrode and composite material so more energy is transferred between them which leads to increasing SR. Figure 8 shows the plot between Pulse ON time and Current.it is a witness when current and pulse ON time are increased, SR is decreased. Figure 9 shows that 3D and contour plots for Pulse OFF time and current. It is also noticed that SR increased significantly by the rise in

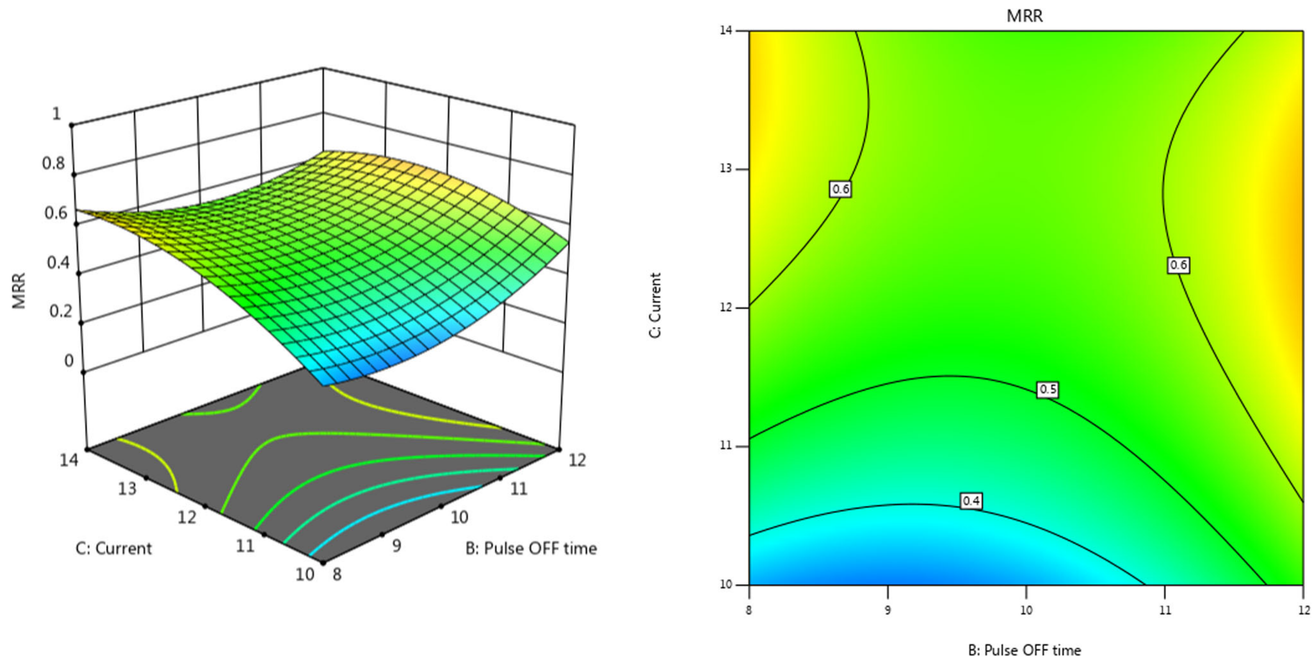

Fig. 6 Pulse OFF time vs. Current on MRR

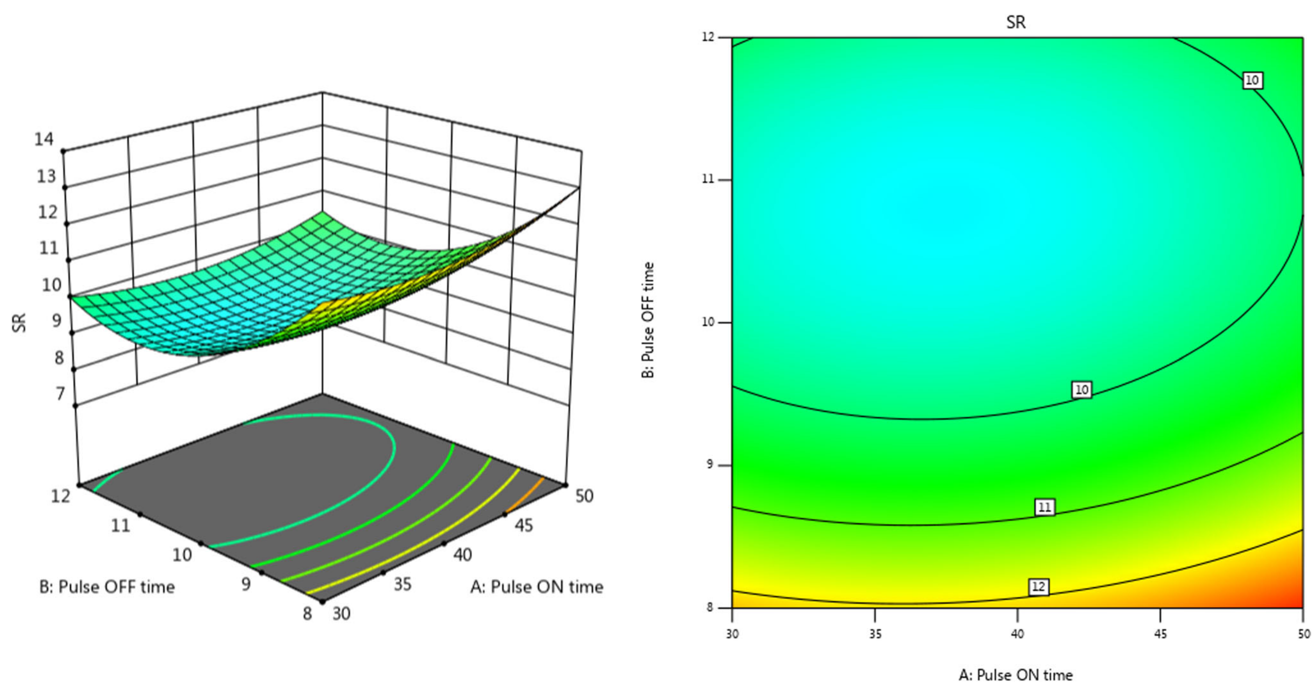

Fig. 7 Effect of Pulse OFF time and Current on SR

Pulse OFF time and decrease of current due to more energy is applied to the gap, lowering its quality. SR reduces as pulse time increases because it keeps the dielectric used for machining at a constant temperature [24]. From these above plots, we found that Pulse OFF time is an important variable to improve SR of prepared composites.

3.4 Predicted vs. actual value plot

An effect of the model is displayed and contrasted with the null model in a predicted against the actual plot. The points should have narrow confidence bands and be relatively near to the fitting line for a successful fit. A scatter plot compares the actual values of MRR and SR to the values that the model

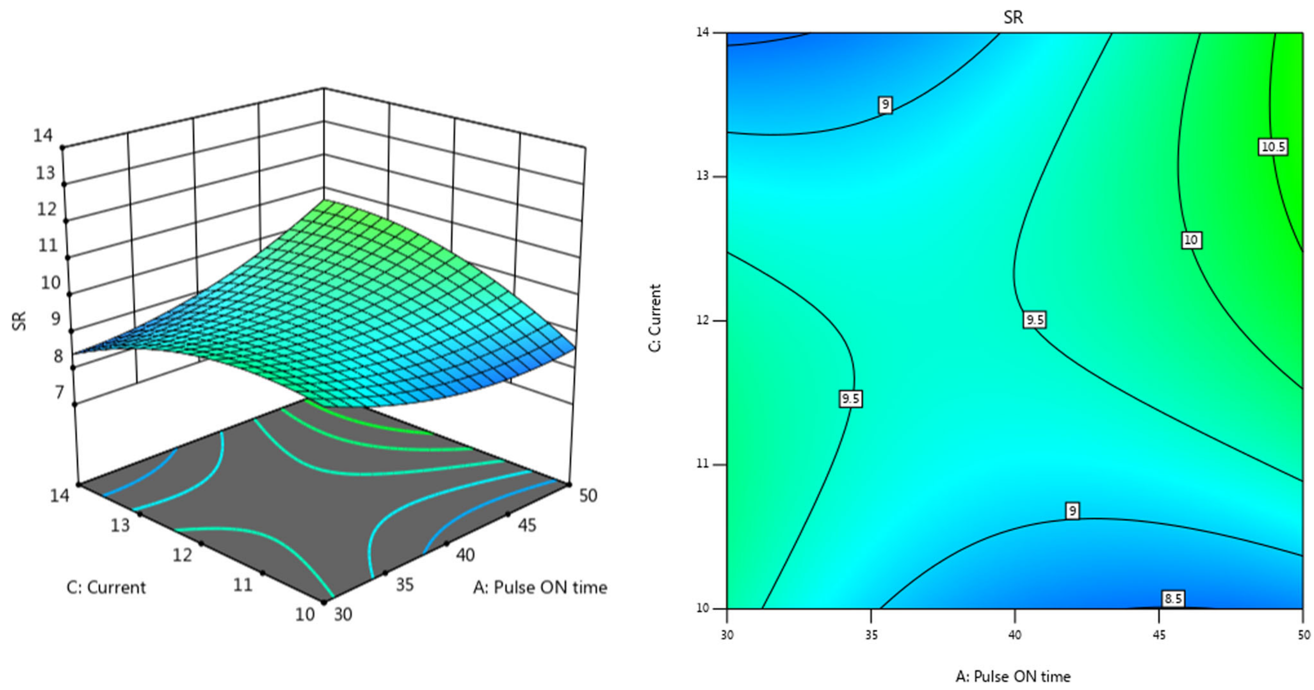

Fig. 8 Effect of Pulse ON time and Current on SR

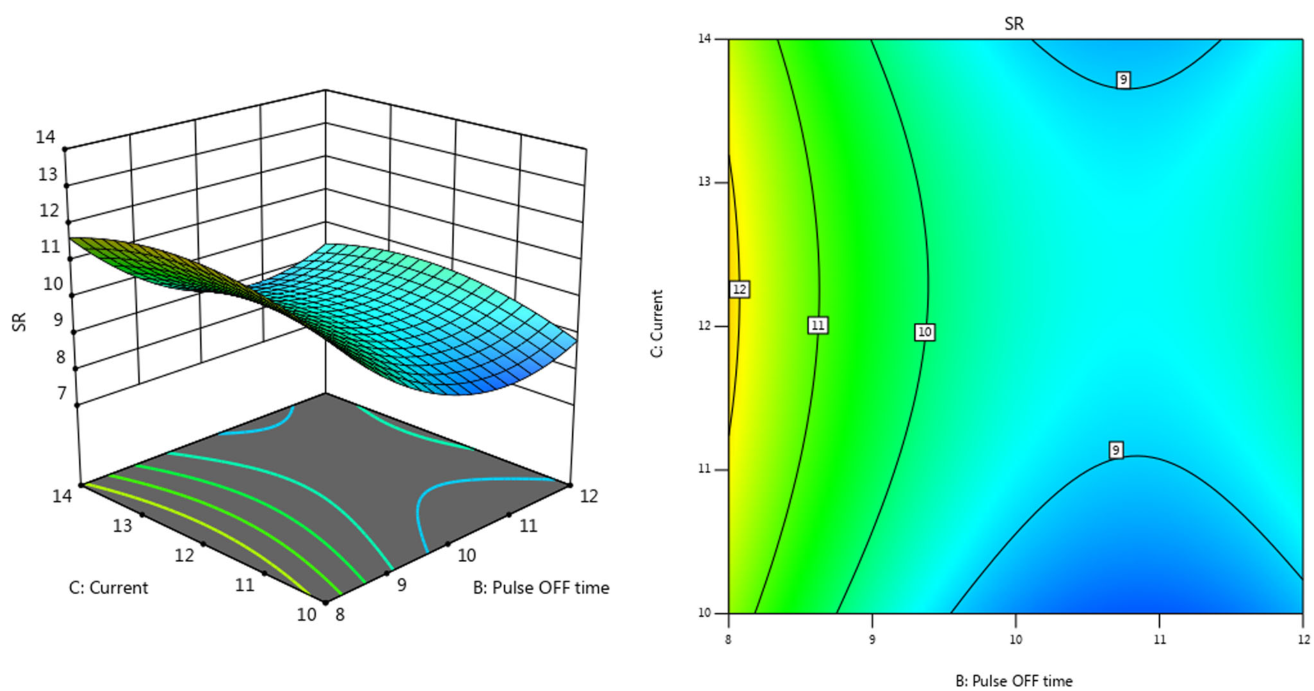

Fig. 9 Effect of Pulse OFF time and Current on SR

predicts. The scatter plot shows the predicted value along the Y-axis and the actual values along the X-axis in Fig. 10. The MRR and SR are very close to each other during observation of Actual with predicted values.

4 Conclusion

The process variables of EDM with RSM-Central Composite Design is studied. The Al5456/ SiC/ Flyash hybrid composites are fabricated by the stir casting technique. The influence of process variables related

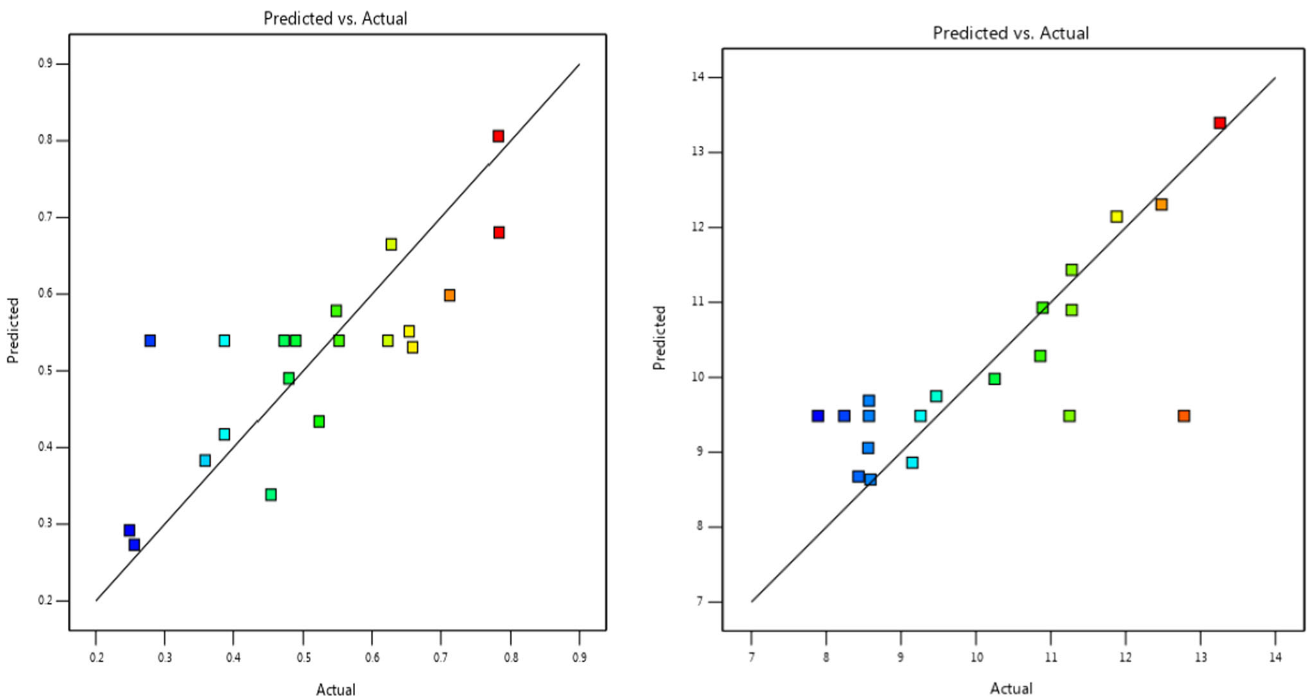

Fig. 10 predicted vs. Actual value **a** for MRR **b** for SR

to EDM including pulse-on time, pulse-off time and current on output variables of MRR and SR for Al composites are examined. The conclusions of the present work are discussed below

- It is observed that the highest (0.783 mm^3/min) and lowest (0.249 mm^3/min) values for material removal rate are acknowledged by Variables A2-B3-C2 (40 µs, 12 µs & 12 Amp) and A1-B1-C1 (30 µs, 8 µs & 10 Amp) respectively. Similarly maximum and minimum for SR are attained by Variables A3-B1-C3 (50 µs, 8 µs & 14 Amp) and A2-B2-C2 (40 µs, 1 µs & 12 Amp) and the SR values are 13.26 µm & 8.24 µm respectively.
- The interaction between two parameters on the MRR and SR is explained through 3D/contour diagrams. The maximum material removal rate is achieved at higher levels of discharge current and low level of pulse OFF time .other hand; the minimum surface is achieved at low levels of discharge current and high level Pulse OFF time.
- The relationship between output responses (MRR and SR) and input machining Variables are analysed.
- ANOVA- quadratic model is selected to develop model for MRR and SR by evaluation of F and *P* tests. Model F-ratio of 4.96 and *P* value of 0.0440 are attained for material removal rate whereas F-ratio of 7.68, and *P* value of 0.02141 are attained for surface roughness.
- ANOVA results show that current and pulse OFF time are high significant variables on the MRR and SR. The development of regression model and 3D/Contour are made to predict and evaluate the Material Removal Surface and Surface roughness.

Acknowledgements The authors appreciate the technical assistance to complete this experimental work from Department of Mechanical Engineering, BVC Engineering College (Autonomous), Andhra Pradesh. The author thanks P V P Siddhartha Institute of Technology, Vijayawada, Andhra Pradesh for the support of draft writing.

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