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A New Hybrid Approach to Optimize the MRR and Tool Wear of EDM for Al/TiC Composites

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Abstract: Electro Discharge Machining (EDM) is extensively used to machine the ceramic composites and electrically conductive materials but due to the abrasive reinforcement, the wear rate may get reduced. This work spotlights on optimizing the developed mathematical models of the Metal Removal Rate (MRR) and Tool Wear Rate (TWR) in terms of machining parameters. The Response Surface Methodology (RSM) (L_{31} empirical model) was used for conducting the basic trails with Al/TiC composites of various compositions. The mechanical and physical properties of Al/TiC composites were analyzed and the SEM morphology of the machined samples was examined using FESEM. The models developed for predicting responses were tested by analysis of variance (ANOVA) to evaluate its adequacy. The optimization of machining parameters was done by Genetic Algorithm (GA) to acquire minimum TWR with maximum MRR.

Keywords: Electro Discharge Machining (EDM); Tool Wear; Metal Removal Rate; Aluminium Matrix Composites; Optimization.

1 Introduction

Electro Discharge Machining (EDM) is extensively used to machine the ceramic composites and electrically conductive materials for making moulds, dies, sections of complex geometry and intricate shapes [1]. Generally, the ceramic composites are Aluminium Matrix Composites (AMCs) in many engineering applications due to its extensive good mechanical and tribological properties [2]. Its tribological properties are improved by graphite addition [3] and its mechanical properties are improved by ceramic reinforcement like SiC, Al_2O_3, B_4C, TiC, TiB_2, MgO, etc [4].

For the commercial applications, TiC was suggested as the suitable ceramic reinforcement in AMCs [5]. The presence of Ti in the matrix had increased the mechanical properties of the composites to a great extent [6]. The improved hardness and strength of the AMC with TiC is becoming complex to machine through traditional methods [7]. In order to overcome the technical difficulties in conventional machining processes, the non-conventional machining processes are increasingly attempted for the machining of carbide ceramics and its composites, particularly for the high dimensional accuracy and complex geometry applications [8].

Among the non-conventional methods, electro-discharge machining (EDM) is the only method capable of machining carbide composites in low cost production [9,10]. EDM is widely used in machining high strength steel, tungsten carbide and thermal conductive materials [11]. From the earlier studies, it was inferred that the EDM process parameters like discharge current, pulse on time, and flushing pressure influences much on the Metal Removal Rate (MRR) and the Tool Wear Rate (TWR) [12].

Design of experiments is a powerful analysis tool for modelling and analysing the influence of control factors on output performance. The traditional experimental design is difficult to be used especially when dealing with large number of experiments and when the number of machining parameter was increased [13]. The most important stage in the design of experiment lies in the selection of the control factors [14]. Gopalakannan et al. [15] had optimized the process parameters of EDM for Al 7075/B_4C composites using response surface methodology (RSM) and inferred that pulse current

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influences the MRR significantly. Wang et al. [16] combined the ANN and genetic algorithm (GA) to find an integrated solution to the problem of modeling and optimization of manufacturing processes.

This investigation focuses on optimization of MRR and TWR by identifying the optimal process parameters of EDM. The mathematical models are developed for the responses in terms of process parameters using RSM and its adequacy were tested by analysis of variance (ANOVA). Additionally, the statistical model developed was utilized to optimize the process parameters to obtain minimum TWR and maximum MRR using GA.

2 MATERIALS AND METHODS

2.1 Materials

The Aluminum 6061 alloy (Table 1) was selected as matrix material and it was heated in a resistant heat furnace containing a stirrer. The castings were done in a batch of 600g. For 5% of TiC reinforcement, it was introduced into the alloy by the reaction between the molten alloy and the mixture of 5% K2TiF6 and 6g of graphite powders and similarly for 10 and 15wt.%. The salt and graphite powders were mixed in the molar ratio of 1:1.3 [17]. The melt temperature was kept as 900° C. This molten mix was held for about 30 minutes before removing the slag and subsequently poured into a mild steel mould of cylindrical cross section with 30mm diameter. The melt was stirred at regular intervals for distribution of reinforcement in the base metal. Following reaction (1–3) took place before the formation of Al/TiC.

$$3K_2TiF_6+4Al \rightarrow 3Ti+3KAlF_4+K_3AlF_6 \quad (1)$$

$$Ti+3Al \rightarrow Al_3Ti \quad (2)$$

$$Al_3Ti+C \rightarrow TiC+3Al \quad (3)$$

2.2 Electrical Discharge Machining (EDM)

A die sinking EDM machine was used for the machining work. The work piece used for the experiment was Al/TiC composites with varying reinforcement wt. %. The specimens were cut for the thickness of 3 mm with the fine surface finishing. The copper hollow tubes of 3mm diameter were used as electrode. The machining parameters assigned for the process and the optimization was given in the Table 2.

The Material Removal Rate (MRR) was expressed as the ratio of the difference of weight of the work piece before and after the machining to the machining time (equation 4). The Tool Wear Rate (TWR) was expressed as the ratio of the difference of weight of the tool before and after the machining to the machining time (5).

$$MRR = (W_{jb} - W_{ja})/t \quad (4)$$

$$TWR = (W_{tb} - W_{ta})/t \quad (5)$$

3 Results and discussion

3.1 Effect of machining parameters on MRR and TWR

The contour plots were developed to study the interaction effect of controlling parameters on the MRR was shown in Fig. 1 The maximum MRR was identified with the maximum current of 15A and the minimum MRR was identified with the minimum current. The other factors were not influencing significantly on the MRR compared to factor *B*. The contour plots were developed to study the interaction effect of controlling parameters on the TWR was shown in Fig. 2

The similar trends of influencing parameter (Current) on MRR and TWR were noticed. The increase in reinforcement (wt.%) increases the TWR with the constant Pulse on time and Flushing Pressure. The maximum MRR with minimum TWR can be obtained with the minimum current and minimum reinforcement for the constant Pulse on time and Flushing Pressure.

3.2 SEM Morphology

The influence of reinforcement was evident from the Fig. 3 for the Al/TiC composite. The increase in reinforcement the MRR was increased due to the severe damage on abrasive particles which was clearly conformed from Fig. 3(b).

The influence of current was the major criteria for MRR which was evident from the Fig. 4 The increase in current from 5 to 15A, the MRR was increased tremendously (Fig. 4(b)). The white layers were formed at low current supply which may due to the oxidation by ambient condition (Fig. 4(a)).

The pulse on time and flushing pressure doesn't influence much in machining process but little significant changes were evident through Fig. 5 and 6. The increase of these factors decreases the MRR (Fig. 5(b) and 6(b)) which was due the influence of current was much higher compared to these two factors. The flushing pressure was mainly used for the initial pitting and crack propagation (Fig. 6(a)) and the pulse on time was used for easy delamination (Fig. 5(a)).

4 Response surface methodology

The optimization process involves the study on the responses based on the combinations, estimating the coefficients, fitting the experimental data, predicting the response and checking the adequacy of the fitted model [18]. The discharge current, flushing pressure and pulse on time were chosen as the independent variables for the responses MRR and TWR. For this DOE, the three

Table 1: Chemical composition of AA 6061.

Element	Al	Cr	Cu	Fe	Si	Mn	Mg	Zn	Ti
wt.%	96.5	0.375	0.275	0.7	0.6	0.15	1	0.25	0.15

Table 2: Parameters and levels assigned.

S. No	Variable	Parameter	Units	levels	
				Low	High
1.	A	Material	(wt.%)	5	15
2.	B	Discharge current	(A)	5	15
3.	C	Pulse on time	(μs)	50	600
4.	D	Flushing Pressure	(Kgf/cm^2)	3	9

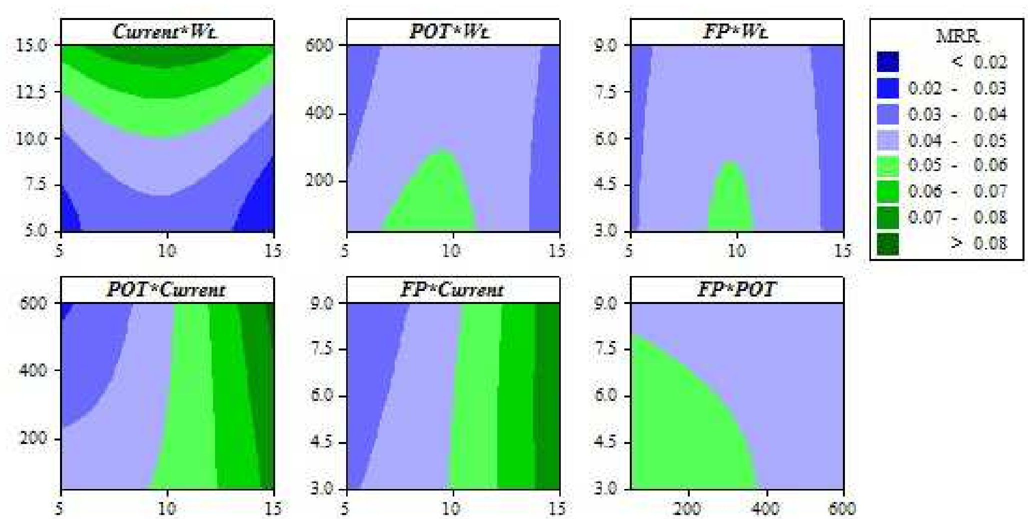

Fig. 1: Contour plots for MRR.

levels RSM design with L_{31} array was done using MINITAB 16.

In order to the combined effects of the independent variables on the responses, a face centred central composite response surface design with 31 sets of experiment with three repetitions were carried out (Table 3). The observed responses were fitted to a second order polynomial model shown in equation (6).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{12} X_1 X_2 \tag{6}$$

where, Y is the observed response; X_1 and X_2 are the independent process parameters; β_0 is the constant; β_1 and β_2 are the linear coefficients; β_{11} is the quadratic coefficients; β_{12}, is the interaction coefficients.

4.1 Mathematical models for the responses

Based on the uncoded data from the given input trails, the mathematical models of the responses were estimated. The MRR in the form of regression equation was stated in equation (7), which states that the factor A and B influences more compared to other factors. For TWR (equation (8)), the factor A and B influences primarily and the factor D influences secondarily.

$$\begin{aligned} MRR = {} & 0.0304378 + 0.00968009 * A - 0.00459533 * B \\ & - 0.000105511 * C - 0.00160405 * D \\ & - 0.000575649 * A * A + 0.000304051 * B * B \\ & + 6.67829E - 09 * C * C - 5.31352E - 05 * D * D \\ & + 2.51625E - 05 * A * B + 3.32941E - 06 * A * C \\ & + 1.30875E - 05 * A * D + 5.12350E - 06 * B * C \\ & + 0.000112346 * B * D + 1.57068E - 06 * C * D \end{aligned} \tag{7}$$

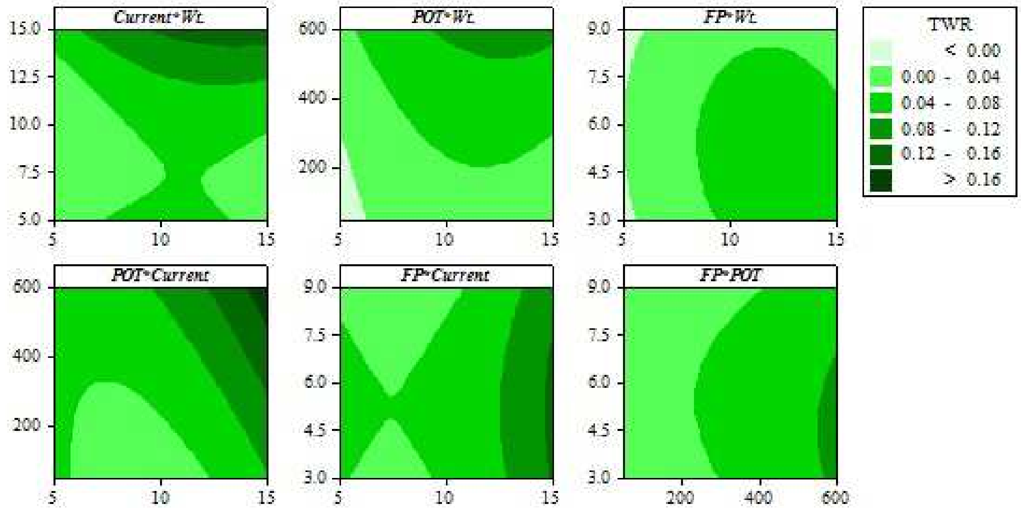

Fig. 2: Contour plots for TWR.

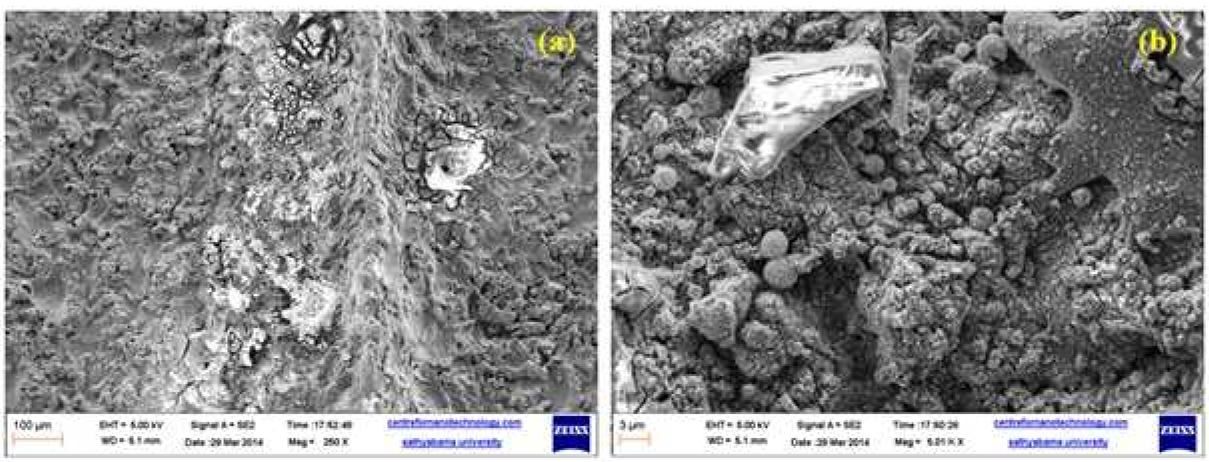

Fig. 3: Effect of reinforcement (a) 5 wt.% (b) 15 wt.%.

$$
\begin{aligned}
TWR = {} & 0.0295402 + 0.0178994 * A - 0.0350752 * B \\
& - 1.32333E - 04 * C + 0.0185184 * D \\
& - 0.00105561 * A * A + 0.00150179 * B * B \\
& + 7.37045E - 08 * C * C - 0.00124613 * D * D \\
& + 0.000732102 * A * B + 5.79395E - 06 * A * C \\
& - 2.83038E - 04 * A * D + 1.75696E - 05 * B * C \\
& - 5.48708E - 05 * B * D - 6.72326E - 06 * C * D
\end{aligned} \tag{8}
$$

4.2 ANOVA

The ANOVA for MRR and TWR were tabulated in Table 4 and 5 respectively. In all forms of regression, the P values of the responses were less than the F value and also it was less than 0.05 i.e. the level of significant was 95%. It confirms that the developed models were adequate, and the predicted values were in good agreement with the measured data.

The adequacy of the responses were tabulated in Table 6 with R^2 and $R^2_{(\mathrm{adj})}$ values. These indicate that the model fits the data well and R^2 was in agreement with $R^2_{(\mathrm{adj})}$ which supports the prediction capacity of the

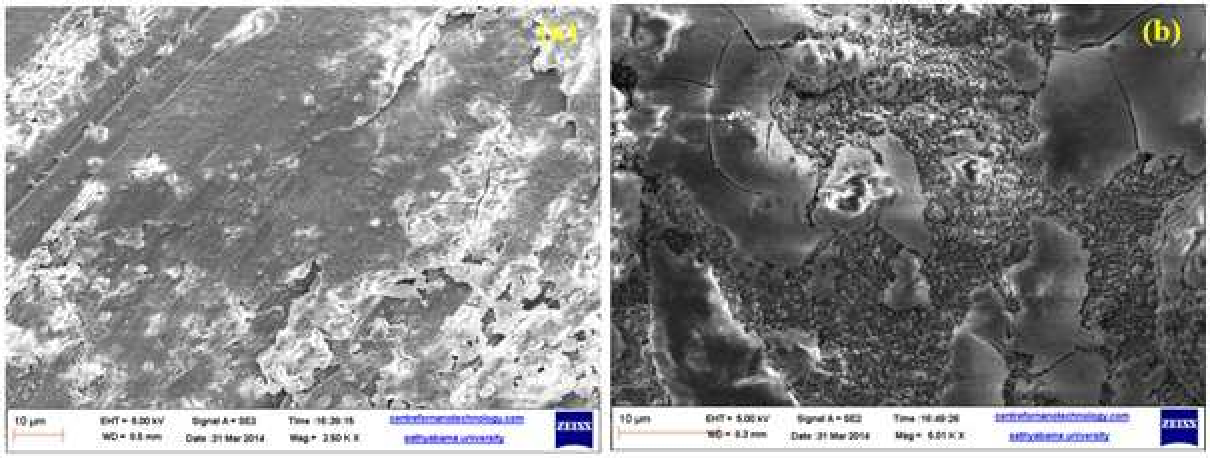

Fig. 4: Effect of current (a) 5A (b) 15A.

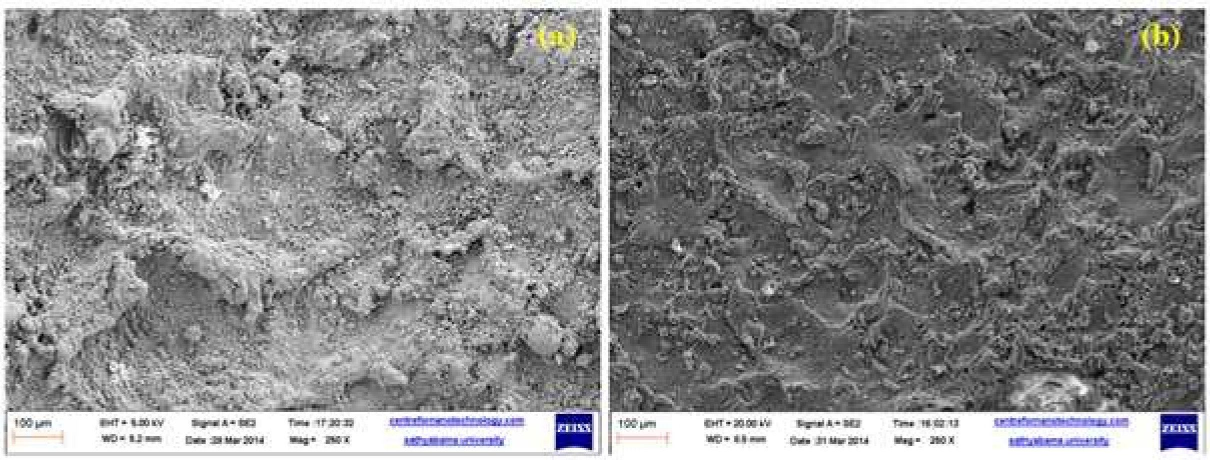

Fig. 5: Effect of pulse on time (a) 50μs (b) 600μs.

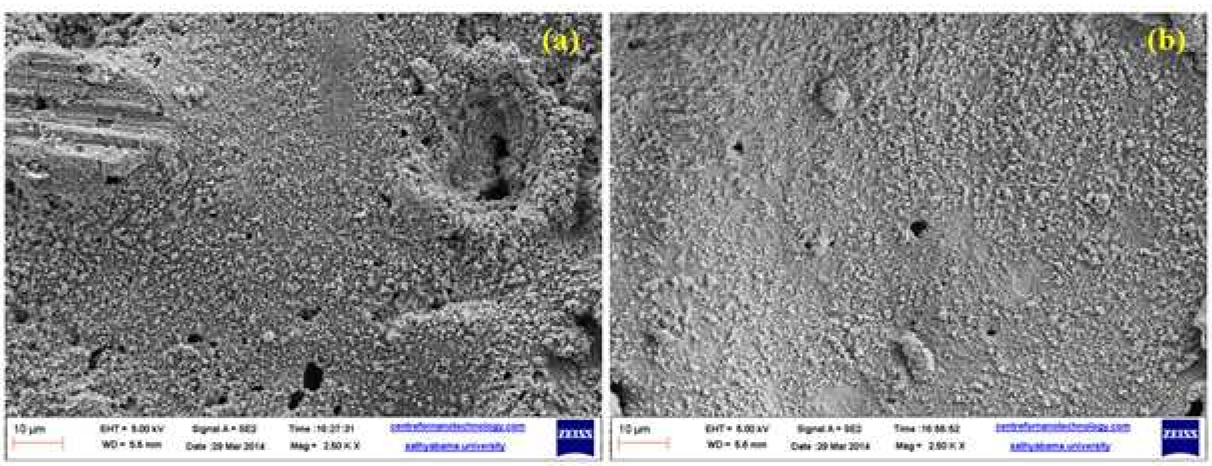

Fig. 6: Effect of flushing pressure (a) 3Kgf/cm^2 (b) 9Kgf/cm^2.

Table 3: Analytical table of responses for the independent variables.

S. No	Wt.(%)	Current (A)	Pulse on Time (μs)	Flushing Pressure (kgf/cm^2)	MRR (g/min)	TWR (g/min)
1	10	10	325	6	0.04825	0.04523
2	15	15	600	9	0.069388	0.176082
3	10	10	325	6	0.04825	0.04523
4	15	10	325	6	0.025519	0.044846
5	5	15	50	3	0.058707	0.006595
6	15	5	50	9	0.027	0.014468
7	15	5	50	3	0.02864	0.01477
8	5	5	600	3	0.015907	0.023099
9	5	15	600	9	0.063456	0.08447
10	10	10	325	9	0.05268	0.03868
11	10	15	325	6	0.090909	0.133
12	10	10	325	6	0.04825	0.04523
13	5	5	600	9	0.008989	0.011635
14	5	15	600	3	0.058636	0.094
15	5	5	50	9	0.027	0.002533
16	10	10	600	6	0.051647	0.09524
17	10	10	325	6	0.04825	0.04523
18	5	10	325	6	0.048405	0.011284
19	5	15	50	9	0.066554	0.021582
20	10	10	325	3	0.04907	0.0478
21	15	15	600	3	0.074	0.227263
22	15	5	600	9	0.017566	0.014189
23	10	10	325	6	0.04825	0.04523
24	10	10	325	6	0.04825	0.04523
25	10	5	325	6	0.027	0.051
26	10	10	325	6	0.04825	0.04523
27	10	10	325	6	0.04825	0.04523
28	15	15	50	3	0.055382	0.068206
29	15	5	600	3	0.01517	0.03581
30	5	5	50	3	0.049	0.001984
31	15	15	50	9	0.046128	0.057923

Table 4: ANOVA for MRR.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	0.009633	0.009633	0.000688	13.34	0
Linear	4	0.007645	0.007659	0.001915	37.12	0
Square	4	0.000779	0.000779	0.000195	3.78	0.024
Interaction	6	0.001209	0.001209	0.000201	3.91	0.014
Residual Error	16	0.000825	0.000825	0.000052		
Lack-of-Fit	9	0.000825	0.000825	0.000092		
Pure Error	7	0	0	0		
Total	30	0.010458				

Table 5: ANOVA for TWR.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	0.071928	0.071928	0.005138	42.21	0
Linear	4	0.050726	0.049948	0.012487	102.58	0
Square	4	0.004698	0.004698	0.001174	9.65	0
Interaction	6	0.016505	0.016505	0.002751	22.6	0
Residual Error	16	0.001948	0.001948	0.000122		
Lack-of-Fit	9	0.001948	0.001948	0.000216		
Pure Error	7	0	0	0		
Total	30	0.073876				

Table 6: Adequacy of the models.

S. No	Response	Std. Deviation	R^2	$R^2_{(adj)}$
1.	MRR	0.007182	92.1%	85.2%
2.	TWR	0.01103	97.4%	95.1%

model. In all the models, both the values were good and above 80% which makes a fitness in predicting solutions.

5 Genetic Algorithm

GA is used to find the optimum configuration of input parameters to achieve the optimal response. In the GA many individuals construct a population to evolve based on described selection rules to state that the fitness gets maximized [19]. GA is of many coded types, here the real coded is used because the inputs are taken from RSM model. The values of initial parameters are tabulated in Table 7 for doing GA in MATLAB 14. The population was supervised by fitness function, which contained three main operators such as crossover, mutation and reproduction.

Table 7: Parameters of GA.

Parameters	Value
Chromosome length	4
Population size	104
Mutation rate	0.2
Selection function	Tournament
Crossover fraction	0.8
Mutation function	Adaptive feasible
Crossover function	Single point

5.1 Optimization of process parameters

For finding the optimal EDM parameters, the generation was started with 0.5 of fitness value and it was increased with a 0.005 step to reach the final value. The generation plot was graphically represented in Fig. 7 This shows the average spread of 0.09 for the maximum generation of 186 and the Pareto chart for the responses were graphically represented in Fig. 8

Among these configurations the possible optimal solutions were generated at 21 plots (Table 8). The optimal process parameters of EDM which can provide maximum MRR and minimum TWR was found from Fig. 9 From the estimated model, the optimal responses were MRR of 0.046381 g/min and TWR of 0.010809 g/min for the optimal process parameters of 5.0000375 wt.%, 10.12719 A, 70.57169 μs, and 3.000981 kgf/cm^2. The same trail of 5 wt.%, 10.13 A, 70.57 μs, and 3 kgf/cm^2 was practically executed to get the practically solution. Its MRR was 0.048 g/min and TWR was 0.012 g/min which were 3.4% and 1.74% deviation from the predicted results but the optimal configuration remains well with the desirability of 98.7%.

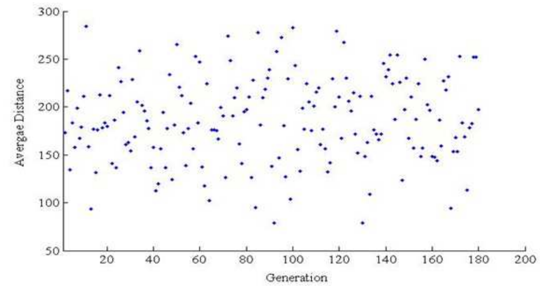

Fig. 7: Generation plots.

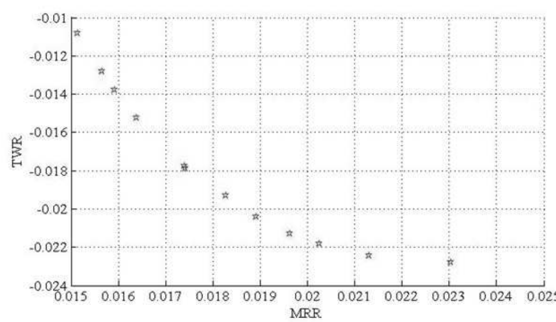

Fig. 8: Pareto Chart.

6 Conclusions

– The Al/TiC composite with varying reinforcement composition was done to study its machining nature was successful.
– The SEM morphology exhibits the influence of parameters on MRR and it evident the current as the major influencing parameter on MRR.
– The mathematical models for MRR and TWR were developed with good adequacy using RSM.
– The maximum MRR of 0.046381 g/min and minimum TWR of 0.010809 g/min for the optimal process parameters of 5.0000375 wt.%, 10.12719 A, 70.57169 μs, and 3.000981 kgf/cm^2 were obtained using GA.
– The responses were 3.4% and 1.74% deviation from the practical results but the optimal configuration remains well with the desirability of 98.7%.

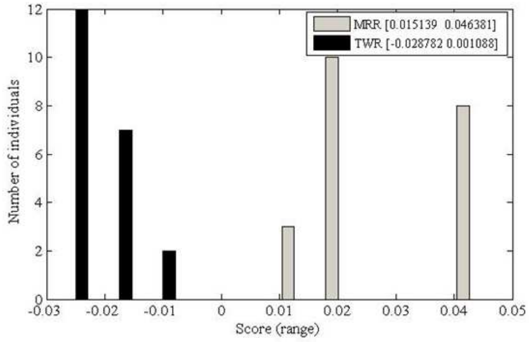

Fig. 9: Optimized results of responses.

Table 8: Optimal configurations of machining parameters.

S. No	Wt.(%)	Current (A)	Pulse on Time (μs)	Flushing Pressure (kgf/cm^2)	MRR (g/min)	TWR (g/min)
1	5.0000375	9.016897	163.958	3.016606	0.040569	0.023069
2	5.0000375	10.12719	70.57169	3.000981	0.046381	0.028782
3	5.0000375	8.310782	72.07169	3.000981	0.043006	0.023978
4	5.0001749	6.024385	466.2136	8.999998	0.017423	0.017867
5	5.0000375	7.845022	466.6355	8.999998	0.023026	0.022778
6	5.0001749	6.824215	466.6355	8.999998	0.019627	0.021263
7	5.0001749	9.266897	163.7705	3.000981	0.041145	0.023492
8	5.0001749	6.324215	464.6668	8.999982	0.01827	0.019282
9	5.0000375	9.516897	73.69669	3.000981	0.044933	0.028131
10	5.0000375	6.005342	465.7136	8.999998	0.017394	0.017737
11	5.0000375	7.345022	466.2136	8.999998	0.021296	0.022414
12	5.0000375	9.095022	71.94669	3.016606	0.04419	0.0271
13	5.0000375	5.380342	466.2605	8.999998	0.015915	0.013754
14	5.0000375	6.574215	466.2136	8.999998	0.018906	0.020398
15	5.0000375	5.255342	466.2136	8.999998	0.015655	0.012807
16	5.0000375	7.845022	466.6355	8.999998	0.023026	0.022778
17	5.0001749	5.005342	466.6355	8.999998	0.015139	0.028782
18	5.0000375	7.024385	466.6355	8.999998	0.020243	0.021808
19	*5.0000375*	*10.12719*	*70.57169*	*3.000981*	*0.046381*	*0.010809*
20	5.0000375	9.016897	73.69669	3.000981	0.043999	0.026921
21	5.0000375	5.587861	466.2136	8.999998	0.016375	0.015214

– This investigation proposed a new approach to find the optimal configuration of EDM process parameters and in future it can be extended to optimize various machining process with multi objective criteria.

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