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A Taguchi coupled desirability function analysis of wire cut EDM behaviour of titanium dioxide filled aluminium matrix composite

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ABSTRACT

The current investigation was, to optimize the parameters for wire cut electric discharge machining (WCEDM) of Al7075 alloy based matrix composite. The Al7075 alloy incorporated with TiO_2 (10 wt.%) particles was produced by stir casting process. Experiments were carried out by selecting the various WCEDM parameters like pulse current (amps), pulse on-time (μs) and pulse off-time (μs). A Taguchi coupled desirability function analysis was employed to determine the optimal parameters with an objective to maximize the material removal rate (MRR) and minimize the surface roughness (SR). The optimum level of WCEDM parameters were obtained by a largest value of composite desirability (d_G). The optimal level of parameters obtained are pulse current at 160 amps, pulse on-time at 120 μs and pulse off-time at 50 μs. Moreover, analysis of variance (ANOVA) was applied to indicate the significant effect of parameters to the output responses. The results observed that, pulse current and pulse on-time are the most impact factors to influence the combined output responses. The contour plot indicates that interaction of machining parameters on the desired output responses.

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1. Introduction

In recent decades, Aluminium Matrix Composites (AMCs) are widely used in various applications like aviation, automotive and marine industries due to their enhanced properties like high specific strength, light density, high hardness, high toughness, low thermal expansion coefficient and good corrosion and wear resistance [1,2]. However, these properties also make composites difficult to machine into a desired shape and sizes, which results in extensive applications have been hindered by high economic machining [3]. During conventional process, a number of problems are occurred like galling, smearing of the cutting tool, which leads to damage of cutting edge and surface damages of the work piece [4]. Thus, there is a need for carrying out non-traditional machining of those composites such as WJM, WCEDM, EBM and LBM etc. [5,6]. Among these non-traditional machining techniques WCEDM is a better option for machining of composites. WCEDM is an efficient cutting process extensively used in the applications like aviation, automotive, nuclear and surgical components with intricate profiles and shapes with high tolerance accuracy [7]. WCEDM is similar to EDM process; it converts electrical energy into thermal energy for eroding the material. The electrodes are immersed in dielectric fluid medium. A very small amount of work materials melt and vaporize by a series of discrete sparks between the tool and work piece [8]. Debris materials are flushed out from the machining area by the dielectric fluid. MRR and SR are very essential output responses [9]. These responses are mainly depends on the various factors such as peak current, spark voltage, pulse-on time, pulse-off time, wire feed rate and dielectric medium [10,11]. To understand the machining behaviour of composites, so far several investigations were attempted the effects of parameters on the MRR and

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SR during WCEDM process [12–14]. Bobbili et al. presented the WEDM process of AA7075 by using brass wire and revealed that the wear rate of brass wire increased when the high electrical energy supplied. They also reported that the higher current and more pulse on-time improved the craters on machined surface [12]. Ramabalan et al. studied the effect of reinforcements and WEDM parameters on MRR of AA7075/TiB_2 composites. They revealed that the higher MRR was achieved by the unreinforced AA7075 when compared with TiB_2 reinforced AA7075 composites [13]. Liu et al. studied the WEDM behavior of Al_2O_3 particles filled AA6061 composites by considering different machining parameters. They explored that applied current was the most essential factor for improving the MRR [14].

In this study, Taguchi coupled desirability function analysis was applied to identify the optimal machining parameters condition for WCEDM process of Al7075-10 wt.% TiO_2 composite. Furthermore, ANOVA was applied to determine the significant effect of involved parameters on the multiple responses such as MRR and SR. Finally, the optimum parameters are verified by conducting the confirmation test.

2. Materials and methods

2.1. Fabrication of composite

In this study, the produced composite consists of Al7075 alloy was used as matrix material and TiO_2 was considered as reinforcement particles. TiO_2 is a better choice for incorporated with aluminium alloys owing to chemical inertness, good wettability, high hardness, superior corrosion and wear resistance. The chemical composition of Al7075 alloy contains (wt.%) are Zn-5.4, Mg-2.42, Cu-1.42, Fe-0.42, Cr-0.21, Si-0.13, Mn-0.12, Ti-0.11 and Al-remaining. The stir casting method was used to fabricate the composite. The measured quantity of matrix alloy was placed in to a graphite crucible and it was melted to 850 °C using electrical furnace. The TiO_2 particles were preheated to a temperature of 200 °C in a muffle furnace. The preheated reinforcement of TiO_2 (10 wt.%) particles were added slowly into the molten matrix alloy. Then the molten mixture was stirred at 280 rpm about 10 min by using mechanical stirrer. After that, the molten mixture was taken outside the furnace and poured in to a preheated mould.

2.2. Machining of composite

The experiments were performed using CNC WCEDM made by ELECTRONICA. The size of composite 100 mm × 100 mm × 10 mm was used as work material. A brass wire having 0.25 mm diameter was used as electrode and their properties are depicted in Table 1. Fig. 1 shows the photographic view of machined composite. During the experiments the influence of MRR and SR of WCEDM on different machining parameters were investigated. In this investigation, the effects of three machining parameters with three levels were selected and are provided in Table 2. An L_9 (3^3) orthogonal array was selected as an experimental layout of WCEDM process. The MRR was determined by difference in weight of the work piece

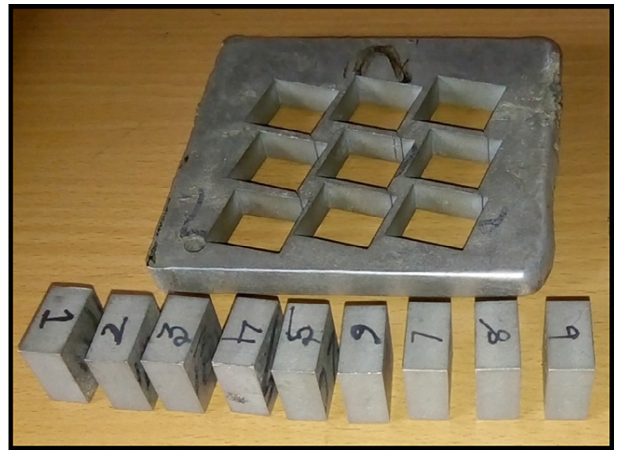

Fig. 1. Photographic view of machined composite.

before and after the cutting process. The surface roughness tester (Mitutoya Talysurf SJ-210) was used to assess the SR value at three different locations on each machined surface of the composite and the average value of SR was considered. The experimental input parameters and output results are depicted in Table 3.

Table 1
Properties of brass electrode.

Property	Value
Density	8.73 g/cm^3
Melting point	940 °C
Specific heat	380 J.kg °C^{-1}
Thermal conductivity	159 W/m-K
Co-efficient of thermal expansion	8.4 × 10^{-6}/°C
Electrical resistivity	4.7 × 10^{-8} Ω.m

3. Result and discussions

3.1. Desirability function analysis

Desirability function analysis was initiated by Derringer and Suich for optimizing the multi-objective characteristics problems [15]. This method is used to convert the multi response characteristics into single response characteristics with the consideration of composite desirability (d_G) [16]. In current study, the multi-responses such as MRR and SR are combined as composite desirability. The steps for desirability function analysis are given:

Step 1: Compute the individual desirability index (di) for all the output responses. There are three types of equations are availed for evaluate the individual desirability index [17].

Larger-the-better: The objective function is to be maximum; Eq. (1) has been used.

$$di = \begin{cases} 1, & \hat{y} \leqslant y_{\min} \\ \left(\frac{\hat{y}j - y_{\max}}{y_{\min} - y_{\max}}\right)^r, & y_{\min} \leqslant \hat{y}j \leqslant y_{\max}, r \geqslant 0 \\ 0, & \hat{y} \geqslant y_{\max} \end{cases} \tag{1}$$

Nominal-the-best: The objective function is a particular target, Eq. (2) was used.

$$d_i = \begin{cases} \left(\frac{\hat{y} - y_{\min}}{T - y_{\min}}\right)^s, & y_{\min} \leqslant \hat{y} \leqslant T, s \geqslant 0 \\ \left(\frac{\hat{y} - y_{\max}}{T - y_{\max}}\right)^t, & T \leqslant \hat{y} \leqslant y_{\max}, t \geqslant 0 \\ 0, & otherwise \end{cases} \tag{2}$$

Smaller-the-better: The objective function is to be minimum; Eq. (3) has been used.

$$di = \begin{cases} 1, & \hat{y} \leqslant y_{\min} \\ \left(\frac{\hat{y}j - y_{\min}}{y_{\min} - y_{\max}}\right)^r, & y_{\min} \leqslant \hat{y}j \leqslant y_{\max}, r \geqslant 0 \\ 0, & \hat{y} \geqslant y_{\max} \end{cases} \tag{3}$$

Here, y_{max} – is the maximum value of 'y', y_{min} – is the minimum value of 'y', T – denotes the target value, s, t, r – weight of responses. In the present study, MRR was considered as the larger-the-better

Table 2
Machining parameters with its level.

Symbol	Machining parameters	Units	Levels		
			1	2	3
A	Pulse current (I_p)	Amps	80	120	160
B	Pulse on-time (T_{on})	µs	110	115	120
C	Pulse off-time (T_{off})	µs	40	50	60

Table 3
L9 design: input parameters and output responses.

Ex. No	Input parameters			Output responses	
	I_P (amps)	T_{on} (µs)	T_{off} (µs)	MRR (g/min)	SR (µm)
1	80	110	40	0.48571	5.217
2	80	115	50	0.49941	3.953
3	80	120	60	0.50332	3.345
4	120	110	50	0.49713	3.416
5	120	115	60	0.50577	3.619
6	120	120	40	0.51042	3.438
7	160	110	60	0.51548	3.583
8	160	115	40	0.50424	3.073
9	160	120	50	0.53677	3.239

characteristics and SR was considered as the smaller-the-better characteristics.

Step 2: Compute the composite desirability (d_G). The composite desirability values were estimated by combining the individual desirability index of each responses and Eq. (4) was used [17].

$$dG = \sqrt[w]{d1^{w1} * d2^{w2} * \cdots * di^{wi}} \quad (4)$$

where, d_i – is the individual desirability index and w_i – is the weight of response.

Step 3: In this step, after getting the composite desirability values, the optimal combination of parameters level can be determined. Generally, the highest value of the composite desirability (d_G) is considered to optimum level of parameters. The calculated composite desirability with order in rank is provided in Table 4.

The composite desirability value for the nine experiments is shown in Fig. 2. From the figure, it can be observed that experiment 9 has the higher value of composite desirability (d_G), which indicates a better combination of optimum level of machining parameters (I_p: 160 amps, T_{on}: 120 µs, and T_{off}: 50 µs) for multi-response characteristics with an objective to maximize the MRR and minimize the SR during WCEDM machining of Al7075-10 wt.% TiO_2 composite.

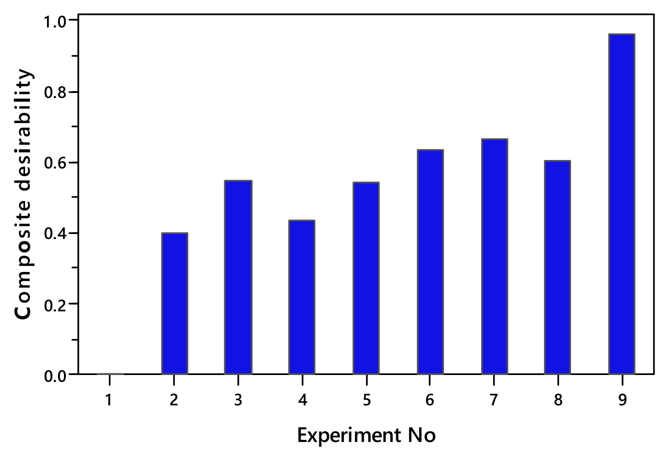

Fig. 2. Rank plot for composite desirability (d_G).

3.2. Analysis of machining parameters on composite desirability (d_G)

The main effect plot of mean composite desirability with different WCEDM process parameters is shown in Fig. 3. From the graph, the dotted line denotes the average value of mean composite desirability value. It is clearly understood from the graph the higher value denotes the anticipated multiple quality characteristics. It was obviously attained that the optimum level of parameter combination are $A_3B_3C_2$, which indicates that the pulse current at level 3 (160 amps), pulse on-time at level 3 (120 µs), and pulse off-time at level 2 (50 µs). This level of machining parameters improves the multi responses of MRR and SR during WCEDM process of Al7075 alloy-10 wt.% TiO_2 composite.

Table 4
Individual and composite desirability with rank.

Ex. No	Individual desirability (d_i)		Composite desirability (d_G)	Rank
	MRR	SR		
1	0.0000	0.0000	0.0000	9
2	0.2683	0.5895	0.3977	8
3	0.3448	0.8731	0.5487	5
4	0.2236	0.8400	0.4334	7
5	0.3928	0.7453	0.5411	6
6	0.4839	0.8297	0.6336	3
7	0.5830	0.7621	0.6665	2
8	0.3629	1.0000	0.6024	4
9	1.0000	0.9225	0.9605	1

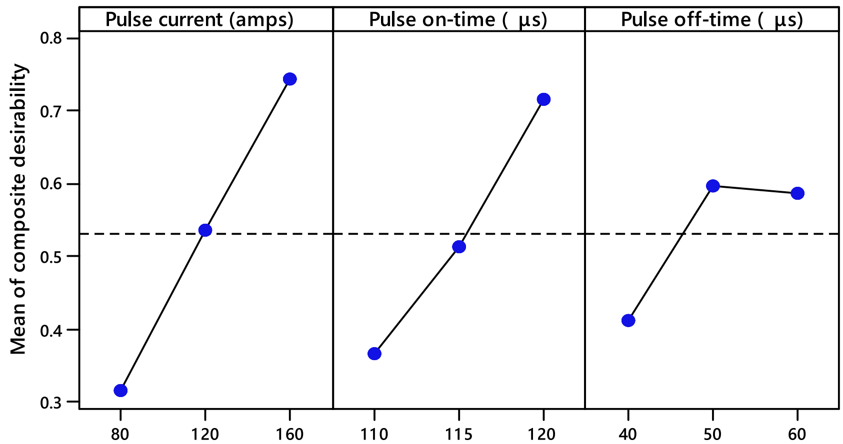

Fig. 3. Main effect graph for composite desirability (d_G).

The mean composite desirability (d_G) for each level of the parameters and the average mean composite desirability are presented in Table 5. From the table, it was observed that the order of influencing machining parameters was determined by the delta value. The maximum value of delta is denoted as rank 1 which indicates that, the parameter is predominant effect on the output response. According to the Table 5, it can be clearly understood that pulse current was the predominant factor on the multiple performance characteristics of developed composite followed by pulse on-time.

3.3. Analysis of variance (ANOVA)

The purpose of ANOVA is to analyze the influence of process parameter along with contributions of combined multiple response characteristics [18]. ANOVA result for composite desirability is given in Table 6. According to the table, it was confirmed that pulse current was the most dominant factor which contributes (51.96%) followed by pulse on-time (34.59%). Pulse off-time is least significant factor on the combined multi response characteristics. The graphical contribution plot is shown in Fig. 4. From ANOVA table, the P-value is less than 0.05 which indicates that the parameter is statistically significant at 95% CI. In this case, pulse current (P = 0.023) and pulse on-time (P = 0.034) have strongly affecting parameter on multiple output responses during WCEDM machining of Al7075-10 wt.% TiO_2 composite. The similar observations were made by Bobbili et al. [19].

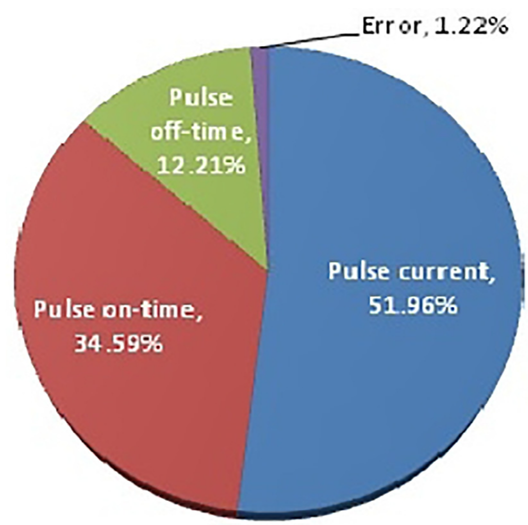

Fig. 4. Contribution of parameters on composite desirability (d_G).

Table 5
Mean table for composite desirability (d_G).

Level	Pulse current (amps)	Pulse on-time (µs)	Pulse off-time (µs)
1	0.3155	0.3667	0.4120
2	0.5361	0.5138	0.5972*
3	0.7432*	0.7143*	0.5855
Delta	0.4277	0.3476	0.1852
Rank	1	2	3
Average composite desirability (d_G) = 0.531584			

* Optimum level.

3.4. Contour plot analysis

Fig. 5(a–c) display the contour plots for composite desirability with machining parameters at varied levels. In Fig. 5(a) represented that the effect of pulse current and pulse on-time on composite desirability. It was observed that the composite desirability value improved when the pulse current and pulse on-time increased. The higher value of composite desirability (0.89) was obtained at the high level of pulse current (160 amps) and the maximum value of pulse on-time (120 µs). From Fig. 5 (b) demonstrated that the effect of pulse current and pulse

Table 6
ANOVA for composite desirability (d_G).

Machining parameter	DF	Seq. SS	Adj. SS	Adj. MS	F-ratio	P-value
Pulse current (A)	2	0.274456	0.274456	0.274456	42.37	0.023
Pulse on-time (B)	2	0.182705	0.182705	0.182705	28.20	0.034
Pulse off-time (C)	2	0.064523	0.064523	0.064523	9.96	0.091
Residual error	2	0.006478	0.006478	0.006478		
Total	8	0.528161				

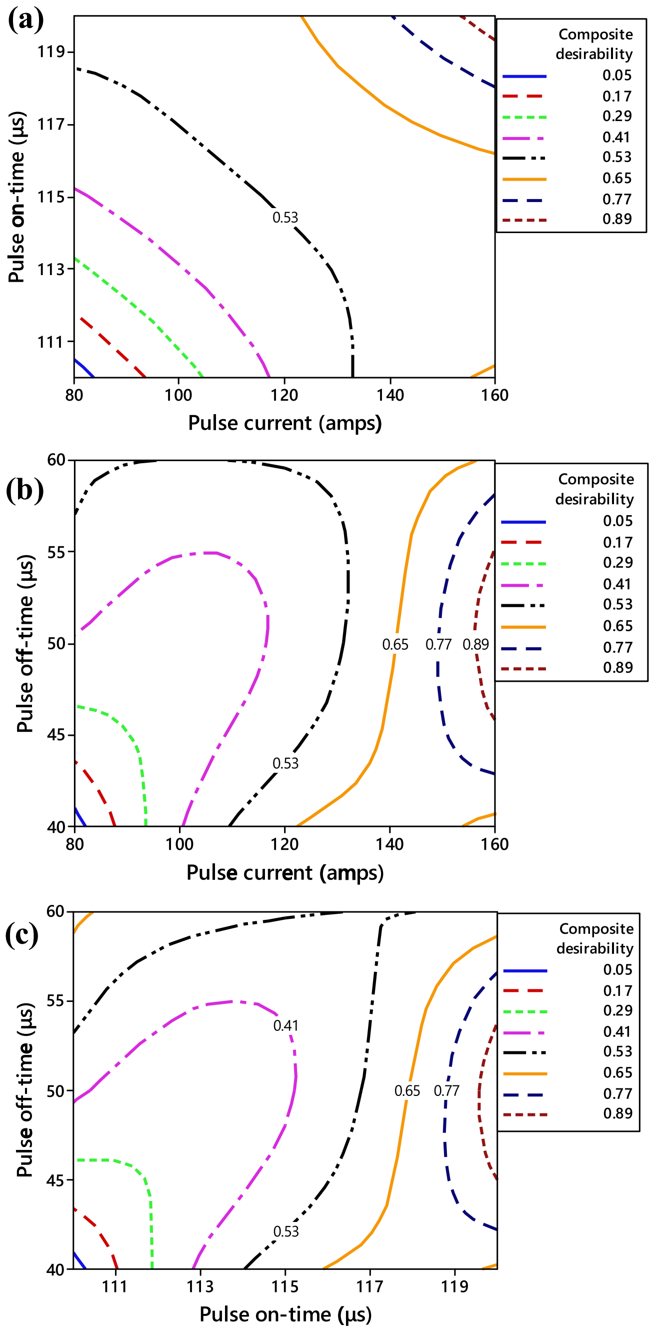

Fig. 5. Contour plot of composite desirability (a) pulse current vs. pulse on-time, (b) pulse current vs. pulse off-time and (c) pulse on-time vs. pulse off-time.

on-time on the composite desirability. It was revealed that the higher setting of pulse current (160 amps) and middle level of pulse off-time (50 µs) gives maximum composite desirability (0.89). For reason is that, the high amount of pulse current generates more heat energy between the electrode and the work piece, thus results in improved the MRR and reduced the SR. In Fig. 5(c), illustrates the response of pulse on-time and pulse off-time on composite desirability. It clearly understood that, the pulse off-time was insignificant parameter, which means the output response doesn't affect during machining process. However, the larger value of pulse on-time (120 µs) increases the composite desirability value (0.89) at any level of pulse off-time remained constants.

Table 7
Confirmation results.

Response parameters	Optimal machining parameter		
	Initial	Predicted	Experimental
Setting level	$A_1B_3C_3$	$A_3B_3C_2$	$A_3B_3C_2$
MRR (g/min)	0.50332	0.53375	0.53677
SR (µm)	3.345	2.8476	3.239
Composite desirability (d_G)	0.5487	0.991532	0.960507
Percentage improvement of composite desirability = 42.87%			

3.5. Confirmation experiments

The confirmation test was employed to validate the experimental results. The optimum level of WCEDM parameters was used to verify the multi response characteristics during machining of Al7075 alloy-10 wt.% TiO_2 composite. The predicted composite desirability value was determined by using Eq. (5) [20].

$$\eta_{preticted} = \eta_m + \sum_{k=1} (\eta_i - \eta_m) \tag{5}$$

where, η_m – denotes the average composite desirability and η_i – denotes the mean value of the composite desirability at the optimum level of parameter and k – is the number of WCEDM parameters. The predicted and experimental value of composite desirability (d_G) is provided in Table 7.

4. Conclusions

- The Al7075 alloy filled with 10 wt.% TiO_2 particles composite was successfully fabricated through stir casting method and the WCEDM process were studied.
- A Taguchi coupled desirability function analysis was effectively employed to find out the optimum level of WCEDM parameters while machining of Al7075 alloy-10wt.%TiO_2 composite.
- The optimal level of WCEDM parameters are pulse current at level 3 (150 amps), pulse on-time at level 3 (112 µs) and pulse off-time at level 2 (50 µs) for achieving maximization of MRR and minimization of SR.
- From ANOVA results observed that, pulse current has the most dominant factor on combined output responses which contributes 51.96% followed by pulse on-time that contributes 34.59%. Pulse off-time has the insignificant factor that contributes only 12.21%.
- The confirmation tests were used to verify the optimal level of WCEDM parameters that improves the percentage of composite desirability value is 42.87%.

CRediT authorship contribution statement

S.V. Alagarsamy: Conceptualization. **M. Ravichandran:** Supervision. **S. Dinesh Kumar:** Methodology. **S. Sakthivelu:** Investigation. **M. Meignanamoorthy:** Writing - review & editing. **C. Chanakyan:** Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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