Hindawi
Journal of Nanomaterials
Volume 2022, Article ID 2903385, 12 pages
https://doi.org/10.1155/2022/2903385

Research Article

Optimization of WEDM Process Parameters in Al2024-Li-Si_3N_4 MMC

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Received 28 February 2022; Revised 8 April 2022; Accepted 11 April 2022; Published 21 May 2022

Academic Editor: Arpita Roy

The present study focuses on optimization of operating parameters in wire electric discharge machining of AA2024 aluminium alloy reinforced with lithium and silicon nitride particles. Aluminium composite was produced through the two-step stir casting route with the combination of 2% lithium and 10% silicon nitride reinforcements. Experiments were performed using the Taguchi design of experiments to optimize the selected input parameters such as pulse on time, pulse off time, current and wire feed for the response parameter, material removal rate, and surface roughness. An ANOVA-based regression equation with genetic algorithm was used to optimize the input variables. The gray relational grade was also performed to optimize multiple performance characteristics. Taguchi-based optimization analysis results in wire feed as the domination factor for material removal rate and surface roughness. Increased wire feed increases the material removal rate with good surface finish as confirmed from gray relational grade analysis. Regression equation generated results with minimum error (<2%) proving the accuracy of the investigation. A genetic algorithm-based study also confirms the analysis of Taguchi and gray relational grade. The wire feed rate at 3 m/min and pulse on time of 120 microseconds were found to be similar for material removal rate and surface finish. Current at 50 A increases the material removal rate and current at 30 A results in good surface finish.

1. Introduction

Advanced composite materials with high strength, high hardness, and light weight finds applications in defense, space craft, and engineering industries [1]. Aluminium composites with SiO2, SiC, B4C, and TiB2 reinforcements has shown remarkable improvements in terms of microstructural, mechanical, and thermal properties. Silica added composite reveals good fluidity with lower stiffness values. Increased heat transfer and wear resistance with better mechanical properties were noticed for the addition of silicon with the aluminium matrix [2, 3]. Machining of such composite materials is difficult in conventional machines and need focus on nonconventional techniques for good surface finish with accuracy. Wire

Figure 1: Prepared specimens for wire electrical discharge machining.

Figure 2: Photograph of Electronica sprint cut CNC wire-cut electrical discharge machine.

electrical discharge machining (WEDM) has shown effective machining methods for composite materials [1, 4]. This machining needs input parameters which are classified as electrical and nonelectrical. The major electrical inputs are current (A), voltage (V), pulse on time (Ton), and pulse off time (Toff). The wire material, wire size, wire feed rate, and dielectric medium are used as nonelectrical input parameters. The major output parameters for optimization are the material removal rate (MRR) and surface roughness (R_a) [5, 6]. The response surface methodology- (RSM-) based Box-Behnken design was used to analyze the output response for surface roughness of aluminium-reinforced silicon carbide (SiC) particles machining using WEDM [7]. Investigation on machining of SiC-reinforced aluminium alloy 2024 composite was carried out and reports suggested that surface roughness is increased for increased pulse on time, and MRR is increased when increasing the pulse on time and peak current [8]. Machining of aluminium 7178 reinforced with 10 wt% ZrB2 composite was made using the Taguchi-based gray rational analysis (GRA) technique. The L16 orthogonal array was used to optimize MRR and R_a with four parameters at four levels. The result showed that the peak current and pulse on time are the influencing parameters for higher MRR and better [9]. The Box-Behnken design with RSM was used to analyze the machining parameters where the increase in pulse on time decreases the surface roughness [10]. In WEDM of Al 6063 with zirconium silicate reinforcement, analysis of variance (ANOVA) concluded that the influencing parameters are peak current and pulse on time [11]. Taguchi's GRA was used to optimize the MRR and surface finish. The results showed that the combined effect of pulse on time, pulse off time, wire tension, and flush rate are essential for a good surface finish with greater MRR [12, 13]. The Taguchi design of experiment (DOE) technique was used to perform experimentation on ballistic grade aluminium alloy using the RSM model [14]. Machining of Al 5083 alloy in WEDM concluded that pulse off time and wire tension does not have any control over surface roughness [15]. An adaptive neuro fuzzy system was used to correlate the relationship between output and input parameters in WEDM of aluminium and SiC composites. The dielectric medium was changed from liquid to gas. Brass wire with oxygen medium was found to have higher cutting velocity [16, 17].

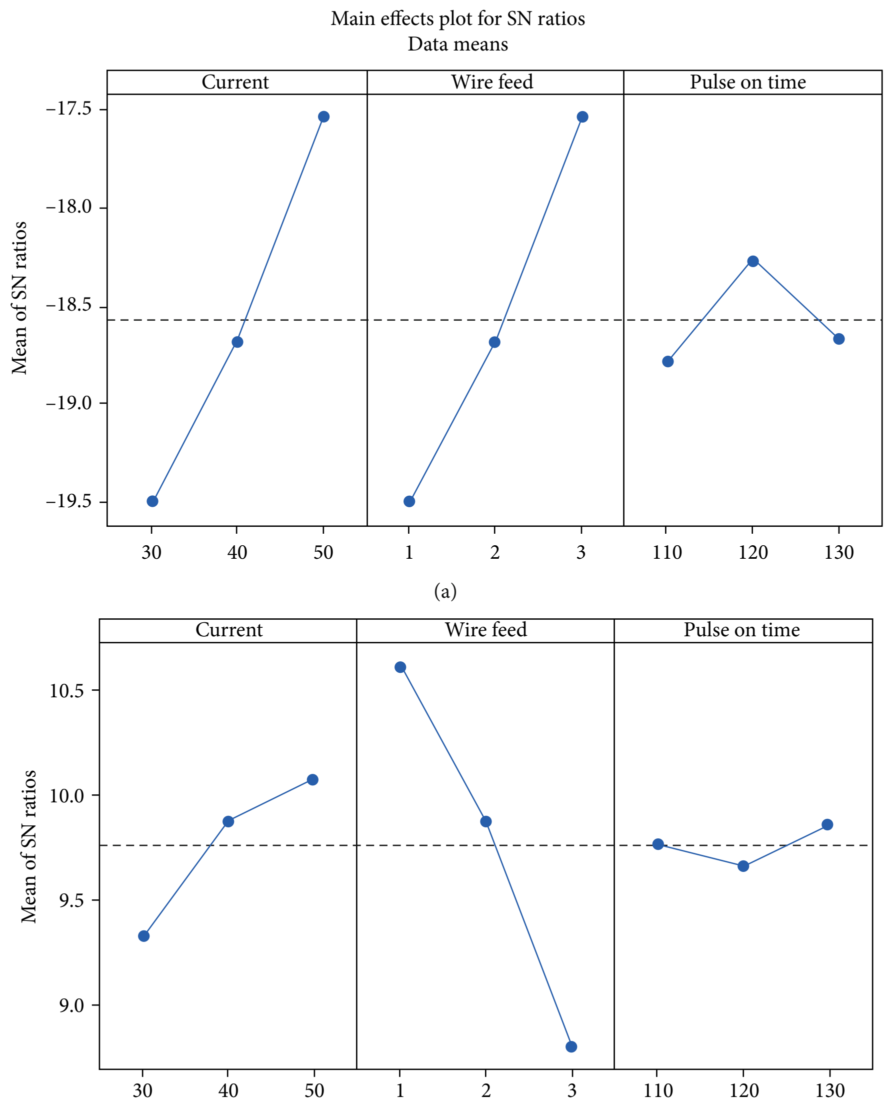
Aluminium alloy 6061 reinforced with SiC was used to optimize the MRR. It was reported that the increase in percentage volume of SiC particle decreases MRR by their study considering L9 orthogonal array [18]. Considering R_a in the WEDM process of Al6061 alloy reinforced with varied 5 to 10 percentage of boron carbide particle, increment in current decreases the surface quality and higher gap voltage increases the surface finish [19]. Machining of maraging steel SS350 was optimized using Taguchi ANOVA-based DOE. In that study, pulse on time, pulse off time, spark gap voltage, and peak current was selected as input parameters. The output parameter selected was MRR and surface roughness. The results clearly indicated that increase in pulse on time and peak current increases the MRR and R_a. It was also observed that the peak current was the most influencing parameter for both MRR and R_a [20]. It was

Table 1: Selected input parameters and its levels.

Factors	Symbol	Unit	Parameter levels		
			Level 1	Level 2	Level 3
Current	I	A	30	40	50
Wire feed	Wf	m/min	1	2	3
Pulse on time	Ton	μs	110	120	130

Table 2: Response values as per L9 design matrix.

Exp.no	Input parameters			Output parameters		Standard deviation	
	I	Wf	Ton	MRR	R_a	MRR	R_a
1	30	1	110	0.09	3.217	0.02	1.13
2	30	2	120	0.11	2.924	0.01	1.12
3	30	3	130	0.12	2.668	0.02	1.11
4	40	1	120	0.11	3.425	0.02	1.12
5	40	2	130	0.11	3.182	0.01	1.12
6	40	3	110	0.13	2.781	0.01	1.11
7	50	1	130	0.12	3.544	0.02	1.13
8	50	2	110	0.13	3.256	0.02	1.11
9	50	3	120	0.15	2.814	0.01	1.11



(b)

Figure 3: Mean effect plot of (a) MRR for S/N ratio and (b) R_a for S/N ratio.

Table 3: Analysis of variance for MRR.

Source	DF	Adj SS	Adj MS	F value	P value
Regression	3	0.002133	0.000711	22.86	0.002
Current	1	0.001067	0.001067	34.29	0.002
Wire feed	1	0.001067	0.001067	34.29	0.002
Pulse on time	1	0.000000	0.000000	0.00	1.000
Error	5	0.000156	0.000031		
Total	8	0.002289			

concluded that MRR is influenced by the wire feed rate and R_a is influenced by pulse on time for the selected input response as pulse on time, pulse off time, and wire feed in machining of SS304 [21]. The Taguchi L18 orthogonal array design was applied for machining Al6061 alloy with the pulse on time, pulse off time, feed rate, and wire tension as input parameters. The output parameter selected for analysis was surface roughness. Results concluded that surface roughness is highly influenced by pulse on time [22]. The Taguchi L9 array type DOE was used for WEDM of AA6082-T6 alloy. Molybdenum was selected as the wire material for the analysis of surface roughness. Results revealed that pulse on time ranked first as the most influencing parameter for minimum surface roughness among pulse off time and current [23]. The Box-Behnken design with the L27 array model was used for machining Al 6061 composite reinforced with graphite and SiC particles. Pulse on time, pulse off time, current, and control speed were taken as input parameters for analysis of cutting speed. From the results, pulse off time was identified as a major influencing parameter on cutting speed followed by the peak current [24]. Pulse on time and current plays a major role towards R_a and kerf width in machining of hybrid Al 7075 composite reinforced with aluminium oxide and silicon carbide particulates using Taguchi GRA analysis [25]. RSM-based Taguchi

Table 4: Analysis of variance for R_a.

Source	DF	Adj SS	Adj MS	F value	P value
Regression	3	0.727592	0.242531	60.05	0.000
Current	1	0.108004	0.108004	26.74	0.004
Wire feed	1	0.616321	0.616321	152.60	0.000
Pulse on time	1	0.003267	0.003267	0.81	0.410
Error	5	0.020195	0.004039		
Total	8	0.747787			

DOE was found to be easy and accurate in the optimization of MRR and R_a as output responses for pulse on time, pulse off time, gap voltage, and peak current as input parameters [26]. Aluminium hybrid composite with fly ash and boron carbide using the Taguchi L9 orthogonal array on the WEDM process was investigated. Four input parameters as pulse on time, pulse off time, wire feed, and gap voltage with three levels was used for the investigation. From the analysis, it was found that gap voltage acts as a dominating parameter towards MRR and pulse off time was significant factor in analyzing R_a [27]. WEDM characteristics on Al 6063 and SiC composites were investigated using the L9 orthogonal array. Pulse on time, pulse off time, wire feed, and gap voltage were taken as input responses and MRR along with R_a as the output response. The result showed that MRR and R_a are highly influenced by pulse on time followed by the wire feed rate [28]. Wire electrical discharge machining of Al/AlCoCr-FeNiMo0.5 metal matrix composite produced by powder metallurgical route indicates that the response parameter MRR and R_a are highly influenced by pulse on time rather than pulse off time and wire feed taken as the input parameter [29]. Increased wear rate was identified for agglomerated silicon carbide and fly ash content within the composite [30]. In electrical discharge machining of aluminium-based metal matrix composite, both current and pulse on time were found to be significant parameter with voltage having no significance [31]. Corrosion studies on Al 7005 alloy reinforced with industrial waste based fly ash and glass fibre showed increased corrosion resistance for composite containing fly ash particles [32]. In machining Al6061/SiC(12%)/Gr(5%) composite using EDM, MRR was found to be increased rapidly for increased current and pulse duration. Copper electrode showed higher MRR compared to brass electrode [33]. Studies on predicting the effect of fly ash on concrete's mechanical properties by the artificial neural network indicated that the mechanical properties of concrete was influenced with fly ash and SiO_2 as reinforcements [34]. From the available literature, it is understood that there has been many results supported in the optimization of machining parameters of aluminium MMC. In this study, an aluminium composite with increased strength and decreased density was aimed for defense, aerospace, structural, and engineering applications. Thus, an attempt was made to machine the aluminium alloy 2024 composite reinforced with lithium (Li) and silicon nitride (Si_3N_4) using WEDM. Taguchi DOE was applied for the optimization of process parameters as it gives the entire study of parameters with low number of experiments. The gray relational grade (GRG) and genetic algorithm (GA) analysis were also conducted and compared with the results of Taguchi optimization.

2. Materials and Methods

2.1. Composite Fabrication. Aluminium alloy 2024 reinforced with Si_3N_4 and Li with weight percentage of aluminium alloy matrix 88%, Li 2% of particle size 50 μm, and Si_3N_4 10% of particle size 70 μm was fabricated through the stir casting route. Direct chilled two-step stir casting under argon atmosphere was selected for manufacturing of composite due to its added advantage in terms of cost and easy processing. Aluminium alloy 2024 was melted in the furnace to a temperature of 760°C temperature. Si_3N_4 reinforcement was added to the melt and uniform mixing was done by continuous stirring for 10 min at 300 rpm. The melt was then transformed to the crucible containing Li and stirred and then transformed to the mould surrounded by cooling water in order to avoid defects in casting. Oxidation of the melt with atmospheric air is controlled by surrounding the melt with argon gas. Thus, a defect free casting was prepared and machined to identify the optimized WEDM process parameters. Figure 1 shows the photograph of prepared specimens for wire electrical discharge machining process.

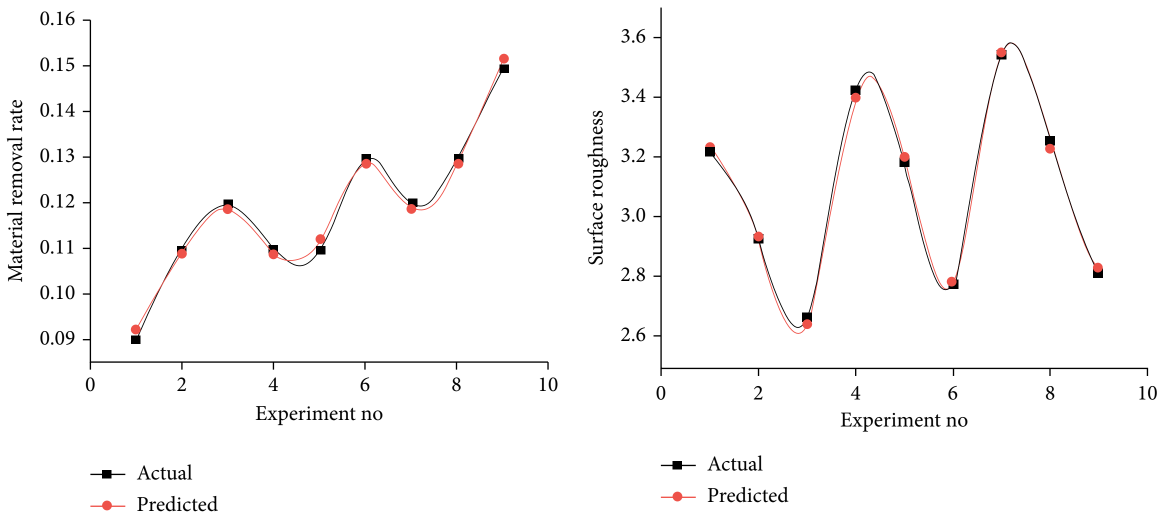
WEDM selected for machining the synthesized composite is best suited to machine hard and complex shapes at faster rate with good accuracy. The experiments were performed on Electronica sprint cut CNC wire-cut EDM as per the design matrix. Brass wire of 0.25 mm diameter was considered the wire material for machining the synthesized composite. MRR is determined by taking the difference in weight of the specimen before and after machining divided by the time taken for the process to complete. R_a is measured directly from the display of surface roughness tester. Three trials of surface roughness values are taken, and the average of the trials is taken as final surface roughness value. Figure 2 shows the photograph of Electronica sprint cut CNC wire-cut EDM used for this study.

2.2. Design of Experiment. Taguchi-based DOE is the best suited optimization technique in minimizing time and cost of experiment with fewer experiments using an orthogonal array design. MRR was calculated by taking the difference between the weight of specimen before machining and after machining with a 0.001 g accurate weighing balance. Performance characteristics are found using the categories larger the better for MRR and smaller the better for R_a. Analysis of variance (ANOVA) is done to confirm the optimum values of input parameters towards better MRR and R_a. The L9 orthogonal array design was selected with 3 factors at three levels [9]. Table 1 shows the selected input parameters and its levels.

2.3. Gray Relational Analysis. GRA is a tool used for optimizing multiple characteristics with huge experimental runs. This method gives a single best optimized response for

Table 5: Regression equation for selected response variable.

Response	Regression equation
MRR	0.11889 − 0.01222 Current_30 − 0.00222 Current_40 + 0.01444 Current_50 − 0.01222 wire feed_1 − 0.00222 wire feed_2 + 0.01444 wire feed_3 − 0.00222 pulse ON time_110 + 0.00444 pulse ON time_120 − 0.00222 pulse ON time_130
R_a	3.0901 − 0.1538 Current_30 + 0.0392 Current_40 + 0.1146 Current_50 + 0.3052 wire feed_1 + 0.0306 wire feed_2 − 0.3358 wire feed_3 − 0.0054 pulse ON time_110 − 0.0358 pulse ON time_120 + 0.0412 pulse ON time_130



(a) (b)

Figure 4: Relationship between observed value and predicted value for (a) MRR and (b) R_a.

Table 6: The gray relational grade for the selected response variables.

Exp. no	MRR		R_a		GRG
	Normalized	GRC	Normalized	GRC	
1	0	0.333333	0.373288	0.443769	0.388551
2	0.333333	0.428571	0.707763	0.631124	0.529848
3	0.5	0.5	1	1	0.75
4	0.333333	0.428571	0.135845	0.366527	0.397549
5	0.333333	0.428571	0.413242	0.460084	0.444328
6	0.666667	0.6	0.871005	0.794918	0.697459
7	0.5	0.5	0	0.333333	0.416667
8	0.666667	0.6	0.328767	0.426901	0.51345
9	1	1	0.833333	0.75	0.875

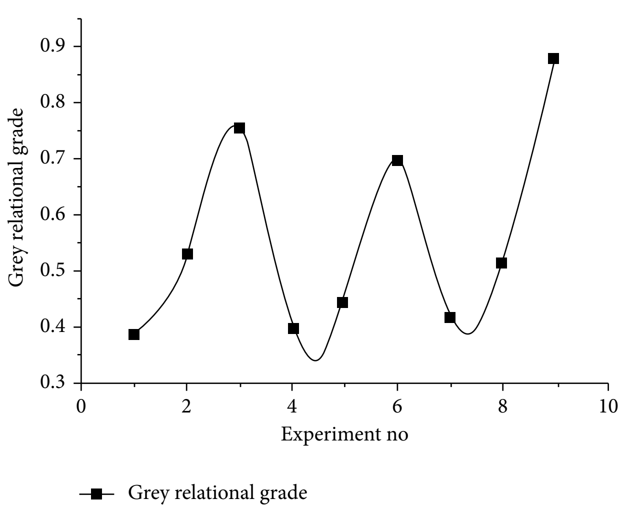


Figure 5: Gray relational grade values for response variable MRR and R_a.

Table 7: Confirmation test results.

S.no	Input parameters			Output parameters		Standard deviation	
	I	Wf	Ton	MRR	R_a	MRR	R_a
1	50	3	120	0.15	2.810	0.01	1.11
2	30	3	120	0.12	2.620	0.01	1.11

multiple experimental runs. Here, larger the better is considered for calculating MRR and smaller the better is considered for calculating R_a.

Normalization of MRR and R_a to the range of 0 and 1 is based on following equations:

$$N_i(x) = \frac{g_i(x) - \min g_i(x)}{\max g_i(x) - \min g_i(x)}. \quad (1)$$

Equation (1) gives the gray relational generation for

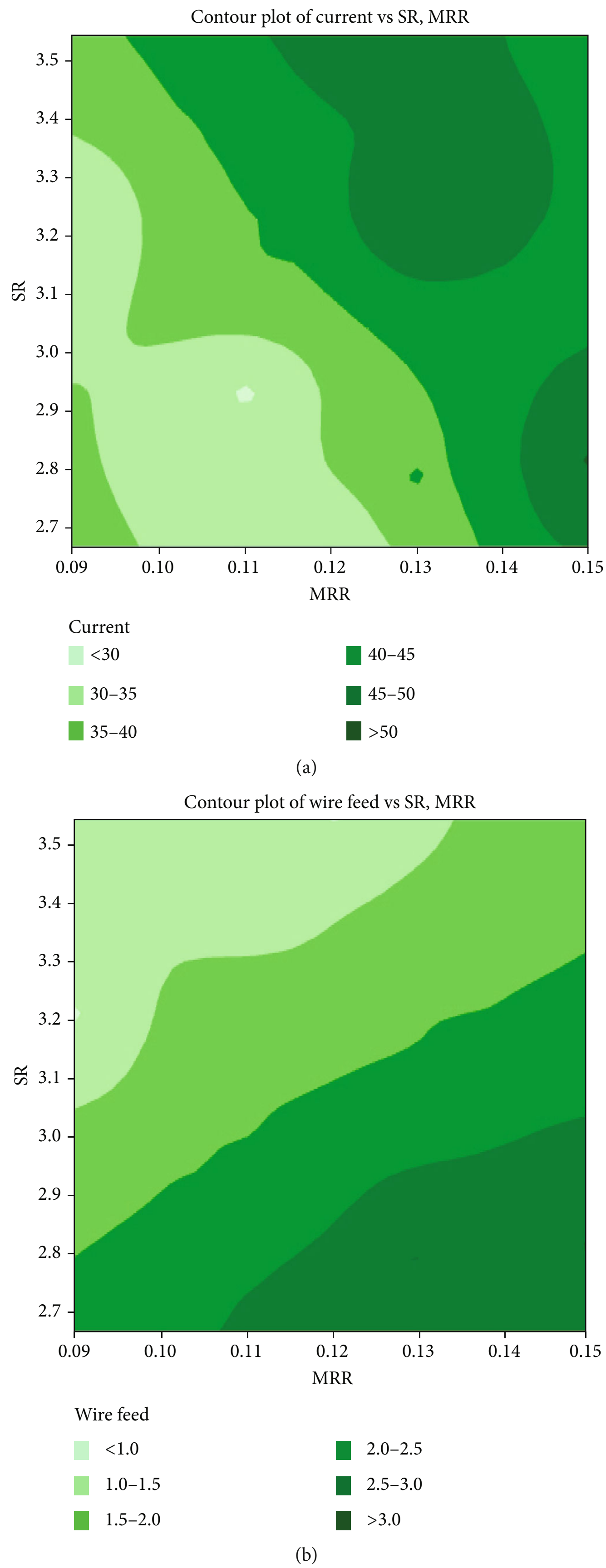
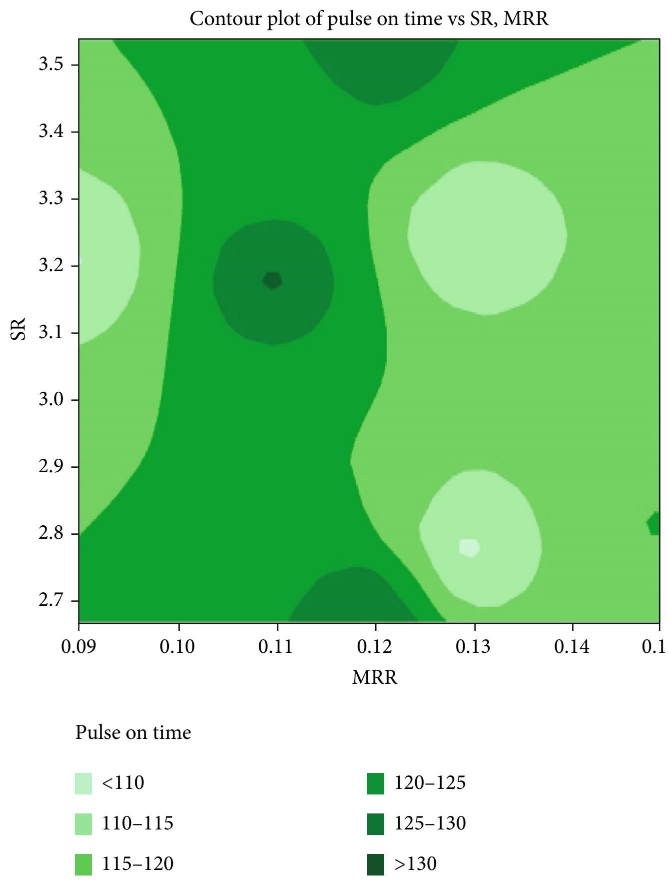


Figure 6: Continued.



(c)

Figure 6: Contour plot of (a) current with MRR and R_a, (b) wire feed with MRR and R_a, and (c) pulse on time with MRR and R_a.

larger the better response.

$$N_i(x) = \frac{\max g_i(x) - g_i(x)}{\max g_i(x) - \min g_i(x)}. \quad (2)$$

Equation (2) gives the gray relational generation for smaller the better response, where $N_i(x)$ = Normalised value of grey relational generation,
$g_i i(x)$ = Value of particular attribute for xth response,
max $g_i(x)$ = Largest value of $g_i(x)$ for xth response, and min $g_i(x)$ = Smallest value of $g_i(x)$ for xth response.

The gray relational coefficient calculated from normalized values is shown in Equation (3) for the weighing factor of 0.5. This shows how closer the variables are for different sequences.

$$\Delta_i(x) = \frac{\Delta_{\min} + \xi \Delta_{\max}}{\Delta_{0i}(x) + \xi \Delta_{\max}}. \quad (3)$$

where $\Delta_{oi}(x) = |N_o(x) - N_i(x)|$, $\Delta_{\max}$ = Maximum value of $\Delta_{oi}(x)$, and $\Delta_{\min}$ = Minimum value of $\Delta_{oi}(x)$.

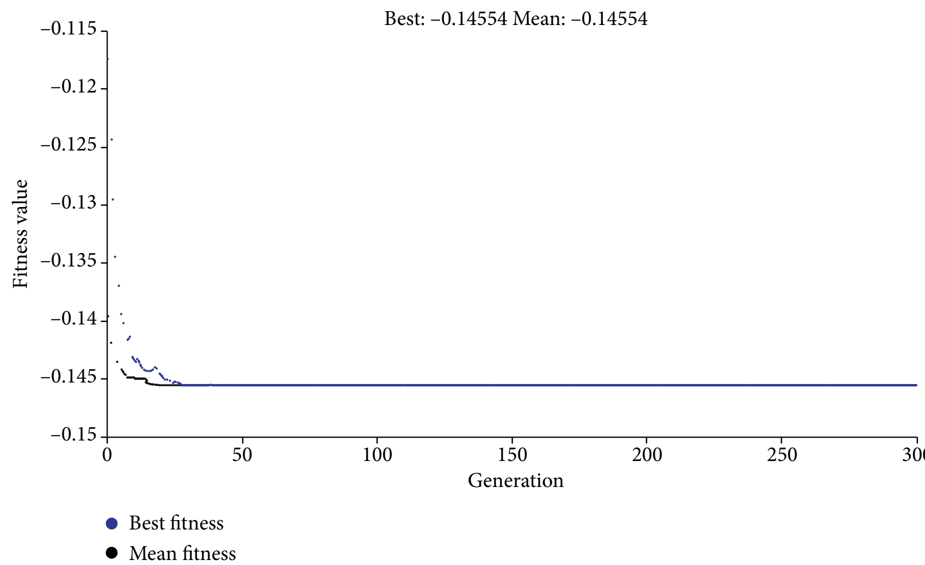
The gray relation grade from the gray relational coefficient is calculated using Equation (4).

$$R_i = \frac{1}{n} \sum_{x=1}^{n} \Delta_i(x), \quad (4)$$

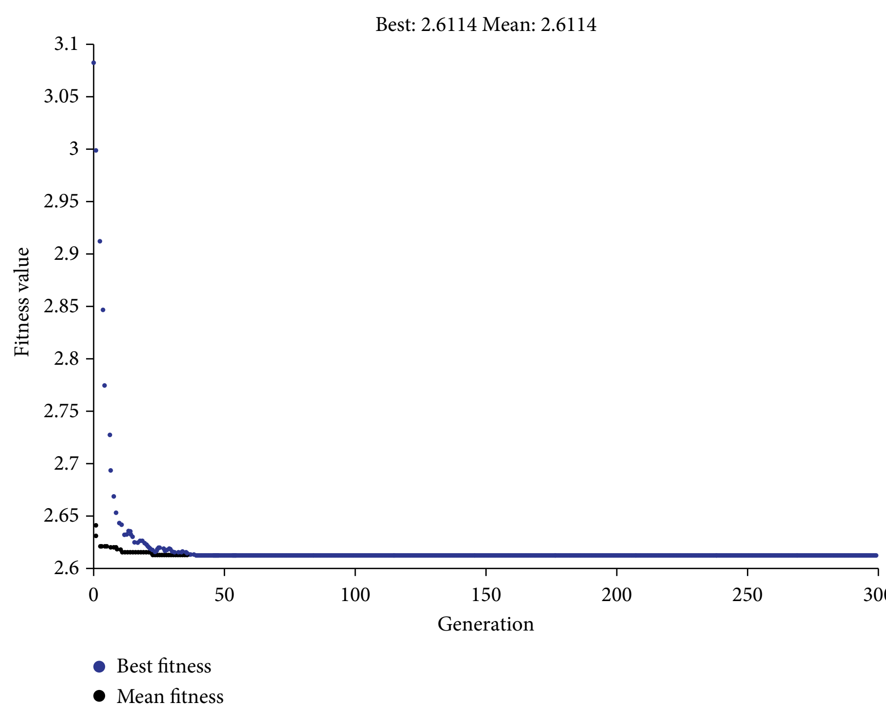
where n is the number of process response.

The set of input parameter levels corresponding to the highest value of the gray relational grade is considered the optimized input parameters for both MRR and R_a. The sequence of optimized levels of input parameters are ranked from highest value to lowest value of the obtained grade relational grade.

2.4. Genetic Algorithm. GA is an optimization technique used to solve lifetime problems with the fastest and easiest method. It is also referred as a search-based techniques to obtain optimal results of difficult problems. Research optimization and machine learning finds these applications to solve complex and difficult problems using natural selections. This process takes a set of input parameters and processes it with required generations to deliver the best optimal results using the fitness equation derived from the regression equations. GA are randomized in nature to solve problems having large search space with more number of



(a)



(b)

Figure 7: Best fitness value of (a) MRR and (b) R_a.

parameters. Discrete and continuous function optimization with multiobjective problems can use this method to obtain good solution with optimum results.

3. Results

The obtained values of MRR (grams per minute) and R_a (microns) during experimentation are presented in Table 2. Input parameters corresponding for higher value of MRR is considered the optimum parameter for this study since the performance characteristics taken is larger the better. Similarly, the input parameters corresponding for lower value of R_a is considered the optimum parameter for this study since the performance characteristics taken is smaller the better.

4. Discussion

Response table for S/N ratio along with delta ranking showed current and wire feed as the most influencing parameter for MRR followed by pulse on time. While considering surface roughness, wire feed ranks as the most influencing parameter followed by current and pulse on time. From the delta rank, it is clearly understood that wire feed and current are the factors to be considered for good accuracy in machining of synthesized composite.

Mean effect plot for S/N ratio of MRR and R_a is indicated in Figures 3(a) and 3(b). From Figure 3(a), current at 50 A, wire feed at 3 m/min, and 120 μs pulse on time is identified as optimized values for better MRR as the performance characteristics of signal to noise ratio is considered as larger the better.

From Figure 3(b), current at 30 A, wire feed at 3 m/min, and 120 μs pulse on time is identified as optimized values for better R_a as the performance characteristics of signal to noise ratio is considered the smaller the better.

Tables 3 and 4 show the ANOVA table for MRR and R_a. The most influencing factor is selected based on P value closer to zero and F value greater than unity.

The results of ANOVA clearly indicate that wire feed and current are closely associated towards MRR, whereas wire feed influences highly for surface finish than all other parameters. Therefore, ANOVA results shows wire feed is the most influencing parameter towards MRR and R_a in machining aluminium composite reinforced with Li and Si_3N_4.

The response variation in percentage is mentioned as R^2 in the model. A better model is selected for higher values of R^2. An adjusted R^2 value displays the accurate model by adding more predictors. The closer the values of R^2 and adjusted R^2 indicate that the registered predictors are correct and accurate. Predicted R^2 indicates the response for new observation with assumptions. Lower values of predicted R^2 compared to R^2 value indicates that the model is with unimportant predictions. The model summary result indicates response variation of 99.03% for MRR and 99.56% for R_a. The adjusted R^2 for MRR and R_a is 96.12% and 98.23% with predicted R^2 value of MRR (80.34%) and R_a (91.04%). Thus, the selected model best suits the experimentation and can be further used for other predictions.

To predict the response values with the actual measured values, regression equations are used. Table 5 shows the regression equation for response variable MRR and R_a. Figures 4(a) and 4(b) displays the correlation between observed value and predicted value of MRR and R_a showing a close relationship tracing the valley and peak of both curves. The minimal error (<2%) proves the accuracy of experiment conducted is accurate and is a generalized form considering all factors.

The gray relational generation is the initial step in which the normalization of values are made to have the output values between zero and one. Table 6 displays the values of GRG for the selected response variables.

Figure 5 represents the grey relational grade values for different experimental runs of MRR and R_a. The highest peak is found on 9th experimental run which represents the optimal levels of input parameter for the selected responses followed by experimental run 3 and 6. Therefore, aluminium composite material with Si_3N_4 and Li are found to have good machining characteristics at pulse on time of 120 μs, wire feed of 3 m/min, and current of 50 A as the optimized parameter for the selected response MRR and R_a. Thus, the gray relational grade optimization and ANOVA results represents the similar set of input parameters and thus proving the accuracy of the investigation.

Confirmatory test conducted for the optimized input parameters shows a close relationship with the obtained experimental values using the Taguchi design matrix. The values obtained in Table 7 confirm the accuracy of the investigation carried out.

Figure 6(a) shows the contour plot of input parameter current for the responses MRR and R_a. Increase in current increases MRR and decrease in current increases the values of R_a. Higher MRR and lower R_a is noted for higher current of 50 A. Figure 6(b) displays the contour plot of input parameter wire feed for the responses MRR and R_a. Increased wire feed rate increases MRR and lowers the value of R_a leading to good surface finish. Wire feed of 3 m/min shows good surface finish with higher MRR. Figure 6(c) shows the contour plot of input parameter pulse on time for the responses MRR and R_a. Increased pulse on time showed lower MRR with good surface finish. Higher MRR and lower R_a is seen for the pulse on time ranging from 120 to 125 μs. Thus, from the contour plots of current, wire feed, and pulse ON time, good surface finish with better MRR is noticed for a current of 50 A, wire feed rate of 3 m/min, and pulse on time ranging from 120 μs to 125 μs. Experimental results of ANOVA, GRG, and contour plots results with the similar set of optimized input parameters confirming the accuracy of studies made on Al-Li-Si_3N_4 MMC.

GA-based trial runs were generated for the fitness function derived from the regression equation using MATLAB R2014 software. The best fitness value for MRR and R_a were identified as 0.14554 grams per minute and 2.6114 microns generated for 300 iterations as shown in Figures 7(a) and 7(b). The values obtained are confirming the experimental results of Taguchi and GRG analysis.

5. Conclusions

From the investigation of aluminium metal matrix composite reinforced with Li and Si_3N_4, the following conclusions were derived:

(1) Aluminium metal matrix composite without defects was fabricated using stir casting technique

(2) Machining parameters for the composite in WEDM was optimized using Taguchi-based DOE using the L9 orthogonal array

(3) Regression equation with gray relational grade and GA was analyzed for the obtained experimental values

(4) Wire feed was found to be the dominating parameter followed by current and pulse on time for MRR and R_a

(5) Higher MRR were identified for the wire feed at 3 m/min, current at 50 A, and pulse on time of 120 μs

(6) Good surface finish is obtained for wire feed at 3 m/min, current at 30 A, and pulse on time of 120 μs

(7) GA-based study also confirms the analysis of Taguchi and gray relational grade. The regression model shows identical values suggesting that the experiment is with minimal error (<2%) in terms of MRR and R_a

Thus, from the obtained conclusions, correlation of Taguchi, gray relational grade, and GA analysis confirms the accuracy of the experimental values obtained in this investigation.

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Disclosure

It was performed as a part of the Mettu University, Metu, Ethiopia.

Conflicts of Interest

The authors of this article declare that we have no conflict of Interests.

Acknowledgments

The authors wish to extend their sincere thanks to Covai wire EDM centre for conducting the machining study and the Department of Mechanical Engineering, Saranathan College of Engineering, for providing surface roughness testing facility. Special thanks to M. Kumarasamy College of Engineering, for giving stir casting facility to carry out this research. Taif University Researcher Supporting Project number TURSP-2020/45, Taif University, Taif, Saudi Arabia, supported this study.

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