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Experimental Investigations and Optimum Performance Evaluation of Wire-EDM Characteristics of Aluminium 6061-Magnesite Composites

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Abstract: It is essential to determine the most suitable machining method for magnesite-reinforced Aluminium 6061 composites, which possess excellent mechanical properties, especially notable tensile strength and hardness. The composites were produced using a stir-casting technique, incorporating reinforcements of lightly-calcined magnesite, dead burnt magnesite, and waste magnesite in weight fractions of 2.5%, 5%, and 7.5% within an aluminium 6061 matrix. Wire electrical discharge machining was employed to investigate the machining characteristics of these composites, using controllable process parameters such as cutting speed, pulse-on and pulse-off times, and the weight fraction of magnesites. Two performance indicators such as surface roughness and material removal rate were tested for various parameter combinations by central composite design. To comprehend the impact of the study parameters, contour charts were drawn. MRR increases at a high cutting speed of 2 mm/min when the pulse-on time changes from 120 μ s to 125 μ s. SR increases when the pulse-on times above 120 μ s at all cutting speeds. High cutting speeds make high MRR irrespective of the weight fractions of reinforcement. High pulse-on times make the material melt more, which increases the material removal rate. Because specimen surface material erodes quickly and forms microcracks, high pulse-on time also results in high surface roughness. To optimize the WEDM machining conditions for each composite, hybrid SSO-DF and DFO-DF optimizers were developed by combining the desirability function with Salp-swarm optimization and Dragonfly optimization algorithms. The cutting speed of 2 mm/min and the pulse-on time of 114 μ s produce the best performances on the composites.

Keywords: WEDM; Al6061-Magnesite composite; material removal rate; surface roughness; Salp-swarm optimization; Dragonfly optimization; desirability function



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1. Introduction

Wire-electrical discharge machining (WEDM) has sparked a lot of industrial interest in recent decades because of its multiple advantages, such as high MRR, low stress and low surface roughness (SR) on the workpiece. Machinability difficulties with aluminium metal matrix composites (AMMCs) by WEDM must be investigated to acquire a better knowledge of AMMCs reliability and manufacturing costs [1,2]. Sidhu et al. (2021) studied the viability of employing electrical discharge machining to machine Al/SiC metal matrix composites [3]. During the electro-erosion machining of AMMCs, the dielectric fluid flushes out the reinforcement materials and facilitates the surrounding alloy matrix melt [4].

Rajesh et al. (2018) examined several electrodes in WEDM for machining Al6061-based composite [5]. The WEDM method is the most feasible machining technique for developing high surface quality AMMCs of complex shapes and sharp edges [6]. Hard ceramic particles in the composites decrease the surface quality and limit the material removal during the WEDM operation, even at greater machining speeds and longer pulse-on times. Hard ceramic reinforcements leave craters, reinforcement debris, and microcracks on kerf surfaces. However, WEDM technology can produce complex geometries of MMCs at a reduced cost [7]. The use of natural ceramic materials as reinforcement particles in aluminium composites improves mechanical characteristics while lowering manufacturing costs. When substances like fly ash, graphite, and powdered granite and marble were used as fortification materials in aluminium alloys, the resulting composites displayed promising characteristics [8–11]. During the sintering process for the preparation of high-quality magnesite grades, i.e., dead burnt magnesite (DBM) and lightly calcined magnesite (LCM), huge chunks of residue materials are dumped as waste. These so-called waste magnetite (WM) particles still contain a significant quantity of magnesium oxide, making them suitable for use as reinforcing particles. All these magnesite grades were chosen as reinforcement particles for the fabrication aluminium composites using stir-casting process [12,13]. The magnesite reinforcements improved the mechanical qualities of aluminium alloy because of the presence of hard magnesium oxide, silica, alumina and some impurities. WEDM is adopted as suitable machining procedure for these composites because of its specific advantages. However, WEDM method has greater operational and investment expenses. Typically, supplier requirements or operator expertise are used to determine the optimum WEDM machining factors to reduce the manufacturing costs. Occasionally, this process might lead to ineffective machining [14]. Thus, using appropriate and intelligent methodologies, the best cutting conditions for the WEDM process should be chosen. In multi-objective optimization research, techniques like the GRA, TOPSIS and PSI methods were also utilized to determine the best EDM parametric conditions for conflicting response combinations [15]. In recent years, lots of research has been conducted on developing meta-heuristic strategies such as Salp-swarm Optimization (SSO) and Dragonflies Optimization (DFO) to optimize engineering optimization problems [16,17]. Both algorithms are fast-convergent and have few parameters. Several engineering applications have demonstrated their effectiveness [18,19]. The Desirability Function (DF) approach was used to perform multi-response optimization and the most desirable parameters were identified for the EDM process [20]. The desirability function was combined with GA, PSO, and Harmony Search (HS) algorithms, resulting in the creation of GA-DF, PSO-DF, and HS-DF optimizers to enhance the non-conventional machining process [21–23]. Based on the literature review, no studies on the machining properties of WEDM for Al6061-Magnesite composites are available. Therefore, the objective is to investigate the impact of WEDM characteristics, specifically Pulse-on Time (T_{on}), Pulse-off Time (T_{off}), Cutting Speed (CS), and Weight Fraction (%) of magnesite particulates in Al6061, on the performance metrics of Material Removal Rate (MRR) and Surface Roughness (SR). Response Surface Methodology (RSM) is employed to model the WEDM characteristics. To identify the best combination of machining conditions for WEDM of Al6061-Magnesite composites, SSO and DFO algorithms are employed in this investigation. The SSO and DFO algorithms are combined with DF to develop SSO-DF and DFO-DF algorithms for the WEDM characteristics of Al6061-Magnesite composites. The experimental results are validated by confirmatory experiments.

2. Materials and Methods

Figure 1 shows the experimental work plan for the WEDM characteristics of Al6061-Magnesite composites.

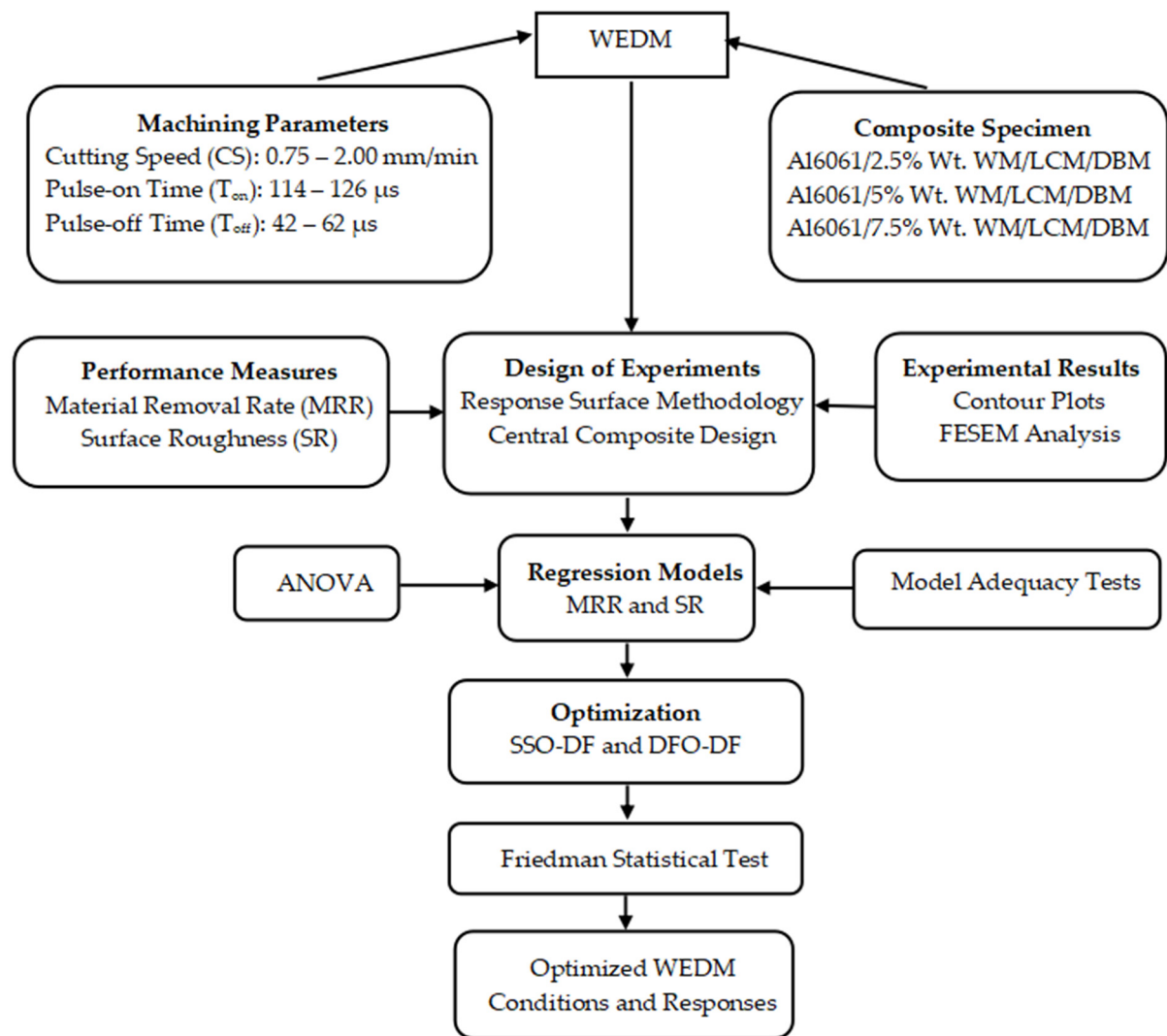


Figure 1. Scheme of the Proposed Work.

2.1. Fabrication of Composites

The stir-casting method is the least expensive way to fabricate AMMCs [24]. Stir-casting of metal matrix composites involves melting a preselected matrix material and adding reinforcing components. Before adding the reinforcing elements, the melt must be properly degassed using an appropriate medium since ambient oxygen oxidizes the molten metal, reducing its characteristics. In bottom pouring method of stir casting, the mould has a pouring aperture at the bottom slightly below the furnace. With this type of arrangement, pouring time is reduced and particle integration is enhanced to result in better composite characteristics. Magnesite powders such as DBM, LCM and WM were preheated to 450° to remove the moisture and enhance the wettability property [12,13]. The aluminium alloy ingots were poured into the stir-casting container and melted at 750 °C. The melt was stirred at 730 RPM for 2 min before adding magnesite powders. Longer mixing times lead to more porosity in the composites, which lowers density and tensile strength [25,26]. Therefore, the composite mixture was stirred for only four minutes. The composite slurry was poured into a mould and allowed to cool. Table 1 lists the fabricated composite grades and their nomenclature.

Table 1. Composite Grades.

Composite Grade	Nomenclature	Density (g/cm ³)
Al6061/Wt. 2.5% LCM	AA-LCM2.5	2.77
Al6061/Wt. 5% LCM	AA-LCM5	2.8
Al6061/Wt. 7.5% LCM	AA-LCM7.5	3.07
Al6061/Wt. 2.5% DBM	AA-DBM2.5	3
Al6061/Wt. 5% DBM	AA-DBM5	2.63
Al6061/Wt. 7.5% DBM	AA-DBM7.5	3.17
Al6061/Wt. 2.5% WM	AA-WM2.5	2.93
Al6061/Wt. 5% WM	AA-WM5	2.97
Al6061/Wt. 7.5% WM	AA-WM7.5	3.07

2.2. Wire-Electrical Discharge Machining

The WEDM setup consists of a machining chamber, pulse power supply, dielectric fluid pumping system, wire tool feeding system, and control panel. The studies were carried out using an Electronica sprintcut-win WEDM with a traverse capacity of 300×400 mm. The controller has an input accuracy of 0.001 mm. DC electricity with a high voltage is applied across the workpiece and wire electrode. The energy discharge in the working gap creates the sparking that melts the workpiece. The dielectric fluid (de-ionized water) flushes the particles out of the machining gap. After filtering, this dielectric is pumped back for more machining. A brass wire-electrode diameter of 0.18 mm was used in this study. In this experiment, deionized water was employed as a dielectric fluid. The dielectric fluid facilitates spark ignition and conductivity as a conducting medium. It helps to lower the temperature of the specimen and tool-electrode and avoid arcing.

Table 2 lists the WEDM setup's machining parameters. The WEDM process involves pulse-on and pulse-off times, gap voltage, current, and other factors. These process parameters are used in most WEDM technologies and research works. High pulse-on duration and current are the source of the specimen's significant electrode wear and excessive surface roughness [27]. The ceramic reinforcement fractions are also noted to be vital in the surface quality of the specimen. Process parameter settings such as current, pulse-off time and working voltage showed a vital influence on the surface finish of the specimen. It could be understood that both MRR and SR increase due to high sparking energy with an increase in current. Considering the above characteristics and machining constraints, several pilot trials were conducted. Finally, the cutting speed, pulse-on and pulse-off times and weight fractions of magnesite particulates were chosen as controlling parameters to investigate the WEDM characteristics of the Al6061-Magnesite composites. Central Composite Design (CCD) was used to conduct the WEDM trials. Table 3 displays the WEDM experimental process variables considered for this investigation. A voltage of 100 V is recommended for this operation since greater voltages result in better WEDM machining rates. A pulse current of 24 A is employed because it produces a strong pulse and causes less significant grain attack on the specimen. The experimental design in Table 4 is followed for machining of the specimen in WEDM. The responses, i.e., MRR and SR, were measured for each of the different parameter settings specified in the CCD.

Table 2. The WEDM Conditions.

Process Variables	Values
Applied Current	3–24 Amp
Gap voltage	0–230 V
Dielectric fluid	Deionized water
Flow rate of dielectric	9 L/min
Dielectric tank capacity	200 L
Flushing pressure	0.5 kgf/cm ²
Electrode	Brass wire of dia 0.18 mm
X-movement	400 mm
Y-movement	300 mm
Z-movement	300 mm

Table 3. Experimental process variables.

Parameters	Notations	Levels		
		1	2	3
Cutting Speed (mm/min)	CS	0.75	1.35	2
Pulse-on Time (μ s)	T _{on}	114	120	126
Pulse-off Time (μ s)	T _{off}	42	52	62
Wt. fraction of magnesite in Aluminium 6061 Alloy (%)	LCM, DBM, WM	2.5	5	7.5

Table 4. Experimental observations of machining Al6061-Magnesite Composites by WEDM.

Exp. No.	CS (mm/min)	T _{on} (μ s)	T _{off} (μ s)	Wt. of Magnesite (%)	Case#1: AA-WM Composite		Case#2: AA-LCM Composite		Case#3: AA-DBM Composite	
					MRR (g/min)	SR (μ m)	MRR (g/min)	SR (μ m)	MRR (g/min)	SR (μ m)
1	1.35	120	52	5	0.031	4.391	0.026	3.998	0.028	3.689
2	1.35	120	52	5	0.030	4.461	0.028	4.016	0.027	3.686
3	0.70	114	62	7.5	0.016	3.515	0.025	3.641	0.022	3.698
4	1.35	120	52	5	0.029	4.401	0.025	3.995	0.028	3.688
5	1.35	114	52	5	0.036	4.403	0.022	3.737	0.027	3.297
6	0.70	126	42	2.5	0.022	5.231	0.026	4.898	0.021	3.911
7	1.35	120	52	5	0.028	4.410	0.023	3.997	0.027	3.687
8	1.35	120	52	5	0.031	4.462	0.025	3.999	0.028	3.685
9	0.70	126	42	7.5	0.028	5.520	0.024	5.099	0.019	3.740
10	1.35	120	52	5	0.035	4.421	0.026	3.997	0.028	3.688
11	2.00	126	62	2.5	0.054	4.260	0.053	3.327	0.052	4.327
12	2.00	114	62	2.5	0.049	3.151	0.045	3.030	0.044	3.659
13	2.00	114	62	7.5	0.051	3.353	0.046	3.092	0.049	3.863
14	0.70	114	62	2.5	0.020	2.875	0.019	3.111	0.018	3.234
15	2.00	126	42	2.5	0.051	4.450	0.049	4.007	0.045	4.078
16	2.00	114	42	7.5	0.039	3.681	0.039	3.925	0.040	3.985
17	1.35	120	42	5	0.032	4.620	0.023	4.171	0.024	3.588
18	1.35	120	52	5	0.027	4.370	0.024	3.997	0.028	3.686
19	1.35	120	52	7.5	0.032	4.241	0.034	4.108	0.027	4.295
20	1.35	120	62	5	0.018	3.940	0.028	3.130	0.029	3.579
21	2.00	126	42	7.5	0.056	4.297	0.057	4.535	0.041	3.597
22	2.00	120	52	5	0.049	3.632	0.033	3.804	0.046	3.794
23	2.00	126	62	7.5	0.062	3.710	0.059	3.462	0.050	4.057
24	0.70	126	62	7.5	0.027	4.091	0.024	4.336	0.019	3.970
25	0.70	120	52	5	0.022	4.102	0.014	4.648	0.023	3.638
26	0.70	114	42	7.5	0.020	4.667	0.020	4.341	0.022	4.134
27	0.70	126	62	2.5	0.019	4.406	0.026	4.108	0.022	3.984
28	1.35	126	52	5	0.038	5.381	0.034	4.221	0.027	3.386
29	0.70	114	42	2.5	0.025	3.698	0.014	3.871	0.017	3.897
30	2.00	114	42	2.5	0.053	3.184	0.039	3.709	0.038	3.973
31	1.35	120	52	2.5	0.032	4.040	0.037	3.649	0.028	4.332

The MRR for each machining trial is determined using the weight loss method, as indicated by the Equation (1).

$$\text{MRR} = \frac{\text{Weight Loss}}{\text{Machining Time}} \text{ g/min} \quad (1)$$

The specimen weights were measured using a digital weighing balance (accuracy 0.001 g). The Mitutoyo surface roughness device (sampling distance 10 mm) was used to measure surface roughness values. Each trial was conducted for 10 min. Three separate measurements for both MRR and SR values are made, and the mean value is recorded.

Aluminium-magnesium composite specimen with dimensions of $20 \times 20 \times 20$ mm were used. Brass wire electrode of 0.18 mm diameter was employed. For each experimental run, the machining was done for ten minutes. Thirteen experiments were carried out on the composite specimen following the CCD experimental design. The experimental work was carried out in three case studies as given below.

Case #1: Wire electrical discharge machining characteristics of AA-WM composite

Case #2: Wire electrical discharge machining characteristics of AA-LCM composite

Case #3: Wire electrical discharge machining characteristics of AA-DBM composite

Table 4 presents the experimental observations. Figure 2 displays machined composite specimen.



Figure 2. Machined Composites by WEDM.

2.3. Uncertainty Analysis

Figures 3–5 display the error plots for the experimental runs of wire electrical machining across all composite grades. The percentage error for measuring MRR ranges from 0.4% to 8%, while for SR, it ranges from 0.38% to 2.97%. The variation in MRR measurement is slightly higher compared to SR measurement. These errors stem from various working environmental conditions, WEDM tool vibrations, uneven sparking, and dielectric quality. Nonetheless, most readings have a percentage error of less than 2%, which is considered acceptable.

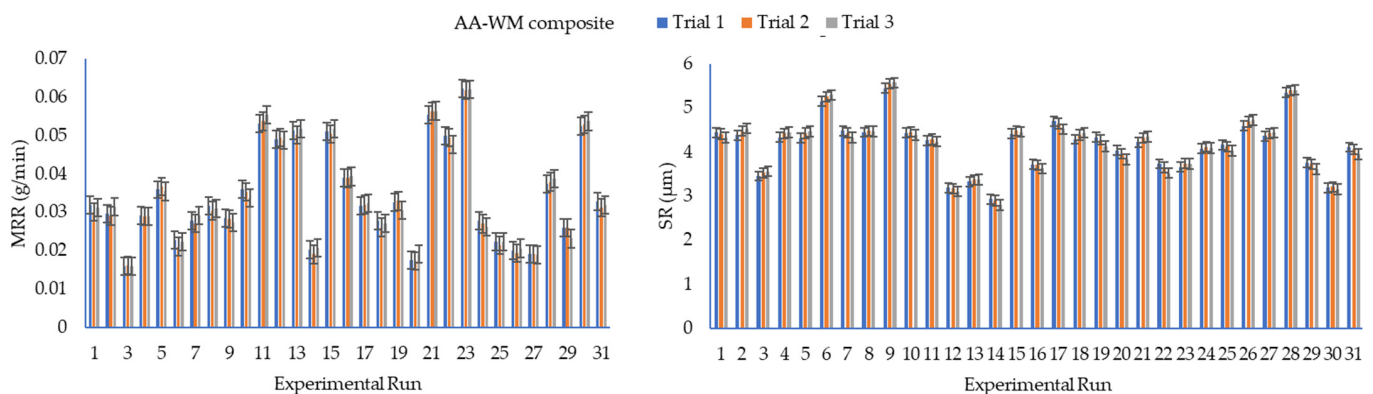


Figure 3. Error plots of WEDM responses for AA-WM composite.

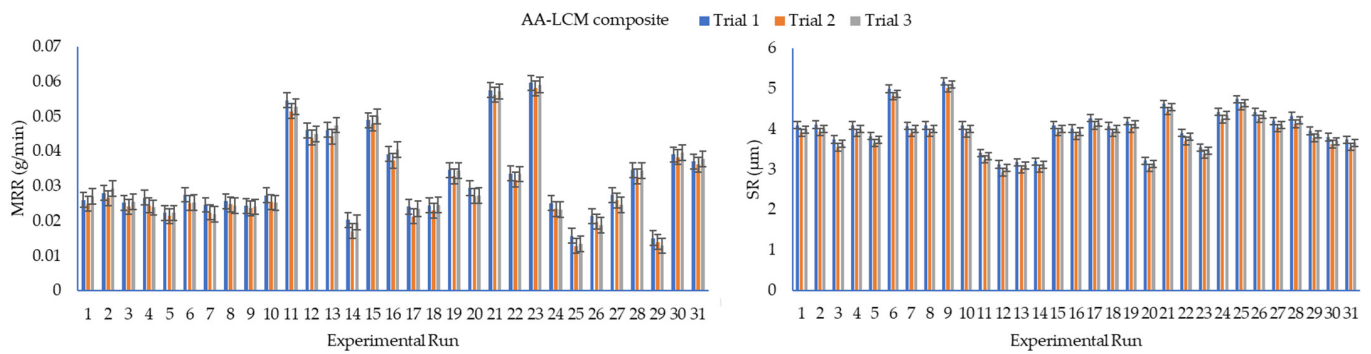


Figure 4. Error plots of WEDM responses for AA-LCM composite.

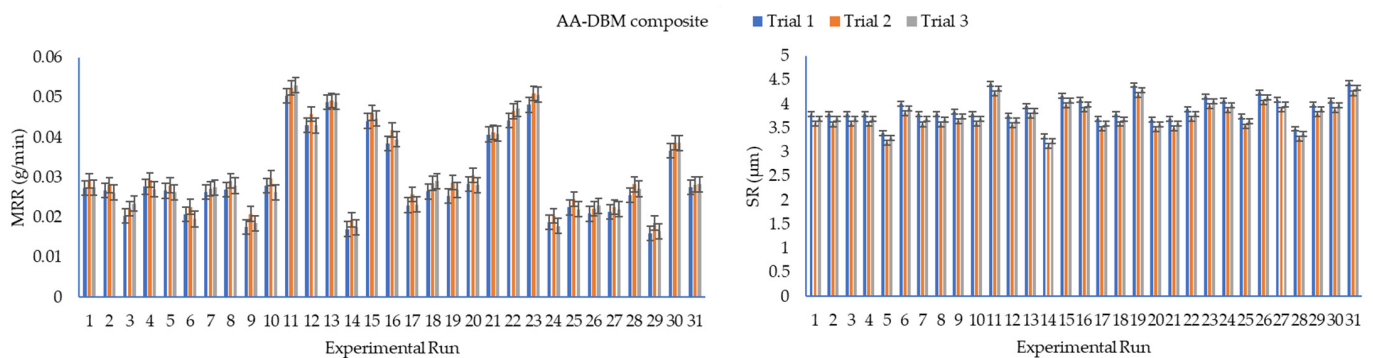


Figure 5. Error plots of WEDM responses for AA-DBM composite.

2.4. Mathematical Modelling and ANOVA

The quadratic equations seemed to be statistically significant after a variety of potential equations fitting the WEDM properties for Al6061-Magnesites composites were examined. There was a 95% confidence interval used in the experiments. In this study, a quadratic equation as in Equation (2) is established using Minitab 20 software, based on the measured responses and their related experimental setting factors.

$$Y = a_0 + \sum_{i=1}^{np} b_i P_i + \sum_{i=1}^{np} \sum_{j=i+1}^{np} c_i P_i P_j + \sum_{i=1}^{np} d_i P_i^2 \quad (2)$$

where, Y —Objective function, a_0, b_i, c_i and d_i —Regression constants, P_i — i^{th} Parameter's value, np —Number of parameters, i —Index value of parameters.

Tables 5–7 provide the analysis of variance (ANOVA) results. Every model has comparatively large F-values. The composites' surface quality and rate of material removal are both highly influenced by the cutting speed, pulse-on and pulse-off durations. The material removal rate is unaffected by the weight fractions of WM, LCM, and DBM. Nevertheless, ANOVA results show that their presence significantly affects the specimen's surface quality. The (-) sign in ANOVA tables signifies that the sources of variation are insignificant to the corresponding response, and therefore, no values were assigned to the respective statistical terms.

Regression Equations (3)–(8) are constructed to depict the WEDM properties of composites made of Al6061 alloy and magnesite powders. The insignificant terms were removed as indicated in Tables 5–7 after experimenting to fit many models for experimental observations. Slightly high “lack-fit F-values” can be compromised by the high model F-values for the model Equations (6) and (8). All the other models possess statistical significance in all aspects.

Table 5. ANOVA results of MRR and SR models for AA-WM composites.

Source	DF		Adj SS		Adj MS		F-Value	
	MRR	SR	MRR	SR	MRR	SR	MRR	SR
Model	9	14	0.004473	11.3136	0.000497	0.80811	24.01	460.48
CS	1	1	0.003901	1.0692	0.003901	1.06921	188.47	609.25
T _{on}	1	1	0.000128	4.3208	0.000128	4.32082	6.18	2462.08
T _{off}	1	1	0.000006	2.0315	0.000006	2.03146	0.27	1157.56
WM	1	1	0.000002	0.1760	0.000002	0.17602	0.10	100.30
CS × CS	1	1	0.000076	0.7249	0.000076	0.72495	3.67	413.09
T _{on} × T _{on}	1	1	0.000126	0.6397	0.000126	0.63966	6.11	364.49
T _{off} × T _{off}	1	1	0.000081	0.0346	0.000081	0.03464	3.92	19.74
WM × WM	-	1	-	0.1688	-	0.16879	-	96.18
CS × T _{on}	-	1	-	0.0819	-	0.08194	-	46.69
CS × T _{off}	-	1	-	0.5971	-	0.59714	-	340.26
CS × WM	-	1	-	0.1574	-	0.15741	-	89.70
T _{on} × T _{off}	1	1	0.000002	0.0302	0.000002	0.03019	0.11	17.20
T _{on} × WM	-	1	-	0.5765	-	0.57646	-	328.48
T _{off} × WM	-	1	-	0.1650	-	0.16504	-	94.04
Error	21	16	0.000435	0.0281	0.000021	0.00175		
Lack-of-Fit	15	10	0.000394	0.0209	0.000026	0.00209	3.86	1.73
Pure Error	6	6	0.000041	0.0072	0.000007	0.00120		
Total	30	30	0.004908	11.3416				

Table 6. ANOVA results of MRR and SR models for AA-LCM composites.

Source	DF		Adj SS		Adj MS		F-Value	
	MRR	SR	MRR	SR	MRR	SR	MRR	SR
Model	7	7	0.004160	7.19132	0.000594	1.02733	87.81	95.60
CS	1	1	0.002901	1.48035	0.002901	1.48035	428.62	137.76
T _{on}	1	1	0.000387	1.70263	0.000387	1.70263	57.24	158.44
T _{off}	1	1	0.000063	2.97599	0.000063	2.97599	9.27	276.94
LCM	1	1	0.000022	0.44462	0.000022	0.44462	3.32	41.38
CS × CS	1	1	0.000006	0.22329	0.000006	0.22329	0.92	20.78
T _{off} × T _{off}	-	1	-	0.35942	-	0.35942	-	33.45
LCM × LCM	1	-	0.000409	-	0.000409	-	60.44	-
CS × T _{on}	1	1	0.000045	0.22610	0.000045	0.22610	6.68	21.04
Error	23	23	0.000156	0.24716	0.000007	0.01075		
Lack-of-Fit	17	17	0.000140	0.24685	0.000008	0.01452	3.21	278.47
Pure Error	6	6	0.000015	0.00031	0.000003	0.00005		
Total	30	30	0.004316	7.43848				

Table 7. ANOVA results of MRR and SR models for AA-DBM composites.

Source	DF		Adj SS		Adj MS		F-Value	
	MRR	SR	MRR	SR	MRR	SR	MRR	SR
Model	9	12	0.003170	2.23106	0.000352	0.18592	560.12	290.64
CS	1	1	0.002738	0.07056	0.002738	0.07056	4353.47	110.31
T _{on}	1	1	0.000020	0.09534	0.000020	0.09534	31.89	149.04
T _{off}	1	1	0.000080	0.02797	0.000080	0.02797	127.55	43.73
DBM	1	1	0.000001	0.00017	0.000001	0.00017	1.41	0.27
CS × CS	1	-	0.000144	-	0.000144	-	228.37	-
T _{on} × T _{on}	-	1	-	0.33132	-	0.33132	-	517.93
T _{off} × T _{off}	1	1	0.000009	0.02797	0.000009	0.02797	13.54	43.73
DBM × DBM	-	1	-	1.13324	-	1.13324	-	1771.51
CS × T _{on}	1	-	0.000014	-	0.000014	-	22.36	-
CS × T _{off}	1	1	0.000053	0.07142	0.000053	0.07142	83.58	111.65
CS × DBM	-	1	-	0.06904	-	0.06904	-	107.92
T _{on} × T _{off}	-	1	-	0.40545	-	0.40545	-	633.81
T _{on} × DBM	1	1	0.000046	0.21460	0.000046	0.21460	72.45	335.47
T _{off} × DBM	-	1	-	0.03871	-	0.03871	-	60.51
Error	21	18	0.000013	0.01151	0.000001	0.00064		
Lack-of-Fit	15	12	0.000012	0.01150	0.000001	0.00096	3.30	479.28
Pure Error	6	6	0.000001	0.00001	0.000001	0.00001		
Total	30	30	0.003184	2.24257				

$$\begin{aligned} \text{MRR}(\text{AA} - \text{WM}) &= 2.53 - 0.0104 \times \text{CS} - 0.0443 \times \text{T}_{\text{on}} + 0.00474 \times \text{T}_{\text{off}} \\ &\quad + 0.000133 \times \text{WM} + 0.01222 \times \text{CS}^2 + 0.000185 \times \text{T}_{\text{on}}^2 \\ &\quad - 0.000053 \times \text{T}_{\text{off}}^2 + 0.000006 \times \text{T}_{\text{on}} \times \text{T}_{\text{off}} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{SR}(\text{AA} - \text{WM}) &= 174.4 + 3.964 \times \text{CS} - 3.102 \times \text{T}_{\text{on}} + 0.1536 \times \text{T}_{\text{off}} \\ &\quad + 2.2598 \times \text{WM} - 1.251 \times \text{CS}^2 + 0.013791 \times \text{T}_{\text{on}}^2 \\ &\quad - 0.001155 \times \text{T}_{\text{off}}^2 - 0.04081 \times \text{WM}^2 - 0.01835 \times \text{CS} \times \text{T}_{\text{on}} \\ &\quad + 0.02972 \times \text{CS} \times \text{T}_{\text{off}} - 0.06104 \times \text{CS} \times \text{WM} \\ &\quad - 0.000724 \times \text{T}_{\text{on}} \times \text{T}_{\text{off}} - 0.012654 \times \text{T}_{\text{on}} \times \text{WM} \\ &\quad - 0.004062 \times \text{T}_{\text{off}} \times \text{WM} \end{aligned} \quad (4)$$

$$\begin{aligned} \text{MRR}(\text{AA} - \text{LCM}) &= 0.0021 - 0.0236 \times \text{CS} + 0.000191 \times \text{T}_{\text{on}} + 0.000187 \times \text{T}_{\text{off}} \\ &\quad - 0.01692 \times \text{LCM} - 0.00318 \times \text{CS}^2 + 0.001737 \times \text{LCM}^2 \\ &\quad + 0.000431 \times \text{CS} \times \text{T}_{\text{on}} \end{aligned} \quad (5)$$

$$\begin{aligned} \text{SR}(\text{AA} - \text{LCM}) &= -12.33 + 1.595 \times \text{CS} + 0.09241 \times \text{T}_{\text{on}} + 0.294 \times \text{T}_{\text{off}} \\ &\quad + 0.06287 \times \text{LCM} + 0.6 \times \text{CS}^2 - 0.003218 \times \text{T}_{\text{off}}^2 \\ &\quad - 0.03048 \times \text{CS} \times \text{T}_{\text{on}} \end{aligned} \quad (6)$$

$$\begin{aligned} \text{MRR}(\text{AA} - \text{DBM}) &= -0.0541 - 0.06549 \times \text{CS} + 0.000414 \times \text{T}_{\text{on}} \\ &\quad + 0.001464 \times \text{T}_{\text{off}} + 0.01359 \times \text{DBM} + 0.01523 \times \text{CS}^2 \\ &\quad - 0.000016 \times \text{T}_{\text{off}}^2 + 0.000240 \times \text{CS} \times \text{T}_{\text{on}} \\ &\quad + 0.000279 \times \text{CS} \times \text{T}_{\text{off}} - 0.000112 \times \text{T}_{\text{on}} \times \text{DBM} \end{aligned} \quad (7)$$

$$\begin{aligned} \text{SR}(\text{AA} - \text{DBM}) &= -121.46 - 0.2361 \times \text{CS} + 2.187 \times \text{T}_{\text{on}} - 0.2420 \times \text{T}_{\text{off}} \\ &\quad - 0.1319 \times \text{DBM} - 0.009476 \times \text{T}_{\text{on}}^2 - 0.000991 \times \text{T}_{\text{off}}^2 \\ &\quad + 0.10094 \times \text{DBM}^2 + 0.010279 \times \text{CS} \times \text{T}_{\text{off}} \\ &\quad - 0.04042 \times \text{CS} \times \text{DBM} + 0.002653 \times \text{T}_{\text{on}} \times \text{T}_{\text{off}} \\ &\quad - 0.007721 \times \text{T}_{\text{on}} \times \text{DBM} + 0.001967 \times \text{T}_{\text{off}} \times \text{DBM} \end{aligned} \quad (8)$$

For all composite specimens, the MRR and SR models' R^2 values are greater than 90% as given in Table 8. The developed regression models are more closely aligned with the experimental data, as indicated by the R^2 values for the MRR and SR models for the three composites (AA-WM, AA-LCM, and AA-DBM). It indicates the significance of the developed regression models. As a result, the mathematical equations of MRR and SR are further implemented for forecasting the WEDM performances for specific parameter settings.

Table 8. Coefficient of determination (R^2) values for MRR and SR regression models.

Composite Grades		AA-WM	AA-LCM	AA-DBM
MRR model	R^2	0.911	0.964	0.996
	R^2 (adj)	0.874	0.953	0.994
SR model	R^2	0.996	0.967	0.995
	R^2 (adj)	0.995	0.957	0.991

2.5. Multi-Response Optimization

2.5.1. Salp-Swarm Optimization Algorithm

Salp-swarm Optimization (SSO) algorithm is a subset of swarm-based heuristic algorithms [16]. In the optimization problem, SSO simulates the swarming behaviour of salps for food as the search for the global best solution. In the deep sea, salps travel in a swarm known as a salp chain, in which the leader, or first salp, guides the follower-Salps.

The position of the leader is updated as in Equation (9).

$$x_j^1 = \begin{cases} F_j + c_1((ub_j - lb_j)c_2 + lb_j)c_3 & \geq 0 \\ F_j - c_1((ub_j - lb_j)c_2 + lb_j)c_3 & < 0 \end{cases} \quad (9)$$

x_j^1 —Position of lead Salp in the j^{th} variable, F_j —Position of food in the j^{th} variable, ub_j —Upper bound of the j^{th} variable, lb_j —The lower bound of the j^{th} variable.
The coefficient c_1 is calculated based on Equation (10).

$$c_1 = 2e^{-\left(\frac{4 * \text{Current Iteration}}{\text{Maximum No. of Iterations}}\right)^2} \quad (10)$$

where, c_2 and c_3 —Random numbers (0,1). The follower-Salps update their position (x_j^i) as follows:

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}) \quad (11)$$

where, $i \geq 2$, x_j^i — i^{th} follower Salp in the j^{th} variable

Equations (10) and (11) are used to simulate the Salp chains.

2.5.2. Dragonfly Optimization Algorithm

Mirjalili (2016) developed Dragonfly Optimization (DFO) algorithm by inspired from the swarming behaviour of dragonflies. The swarming nature of adult and nymph dragonflies is compared to the exploration and exploitation phases of meta-heuristic techniques. Different phases like separation, alignment, and cohesiveness are mathematically implemented using these two aspects. Separation behaviour is the avoidance of static collisions between neighbours. The alignment demonstrates the way neighbours match each other's speeds. Cohesion is the behaviour of individual dragonflies to gather around the centre of their surrounding neighbours. Any swarm's ability to survive depends on its members' attraction to food sources and ability to divert attention from its foes. These five characteristics i.e., Separation, Cohesion, Alignment, Attraction and Distraction are mathematically modelled in the position update of individuals in swarms. The separation behaviour (S_i) of the i^{th} dragonfly is determined as in Equation (12).

$$S_i = -\sum_{j=1}^N X - X_j \quad (12)$$

where, X —Position of the current dragonfly, X_j —Position of the neighbouring j^{th} dragonfly.

The alignment behaviour (A_i) of the i^{th} dragonfly is calculated as in Equation (13).

$$A_i = \frac{\sum_{j=1}^N V_j}{N} \quad (13)$$

where, V_j —Velocity of the neighbour dragonflies, N —Number of neighbours in the vicinity.

The cohesion factor (C_i) of the i^{th} dragonfly is calculated using Equation (14).

$$C_i = \frac{\sum_{j=1}^N X_j}{N} - X \quad (14)$$

The attraction towards a food source is determined using Equation (15).

$$F_i = X^+ - X \quad (15)$$

where, F_i —Food source (i^{th} dragonfly), X^+ —Position of food source

The distraction outwards a foe is determined using Equation (16).

$$E_i = X^- + X \quad (16)$$

where, E_i —Position of a foe of i^{th} dragonfly, X^- —Position of a foe.

The artificial dragonflies update their position using the step (ΔX) and position (X) vectors in a search space. The step vector represents the direction in which the dragonflies are moving. The step vector update is defined in Equation (17)

$$\Delta X_{t+1} = (sS_i + aA_i + cC_i + fF_i + eE_i) + w\Delta X_t \quad (17)$$

where, s , a , c , f , e and w —weight factors for Separation, Alignment, Cohesion, Food, Enemy and Inertia respectively, t —Current iteration.

The dragonflies update their positions using Equation (18).

$$X_{t+1} = X_t + \Delta X_{t+1} \quad (18)$$

The equilibrium between the exploitation and exploration components of the search is established by a dynamic swarm's capacity to preserve appropriate separation and cohesion. In contrast, a static swarm maintains high cohesiveness and very low alignments to assault targets. The swarming factors are also adjusted to maintain a balance between exploration and exploitation. To further boost the stochasticity of the dragonflies in the search space, the position is updated using a Levy flying function.

2.5.3. Desirability Function

In the desirability function (DF), a unique desirability function with a range of (0,1) is constructed for every objective function variable. The individual desirabilities $d(\text{MRR})$ and $d(\text{SR})$ are calculated using Equations (19) and (20) within the allowable limits.

$$d(\text{MRR}) = \frac{\text{MRR}(x) - \text{MRR}_{\min}}{\text{MRR}_{\max} - \text{MRR}_{\min}} \quad (19)$$

$$d(\text{SR}) = \frac{\text{SR}(x) - \text{SR}_{\max}}{\text{SR}_{\min} - \text{SR}_{\max}} \quad (20)$$

$$D = \sqrt{d(\text{MRR}) * d(\text{SR})} \quad (21)$$

The maximization of composite desirability (D) will be the objective function in the SSO and DFO algorithms.

2.5.4. SSO-DF and DFO-DF Steps

The strategy for the implementation of the proposed algorithms is shown in Figures 6 and 7. The SSO and DFO algorithms were run several times to tune parameters that are shown in Table 9. The objective of this work is to determine the optimal settings by simultaneously maximizing the response MRR and minimizing the response SR. For the SSO-DF and DFO-DF algorithms, MATLAB codes have been developed and executed 30 times.

Table 9. SSO and DFO Algorithm Parameters.

DFO Algorithm		SSO Algorithm	
Parameter	Value	Parameter	Value
No. of dragonflies (nd)	100	No. of Salps (N)	100
Maximum Inertia weight ($W_{\max}$)	0.9	C_1 —Coefficient	$2e^{-(\frac{4+it}{\text{nitr}})^2}$
Maximum Inertia weight ($w_{\min}$)	0.2	C_2, C_3	Random value (0, 1)
No. of Iterations (nitr)	100	No. of iterations (nitr)	100
Archive size	100	Archive size	100

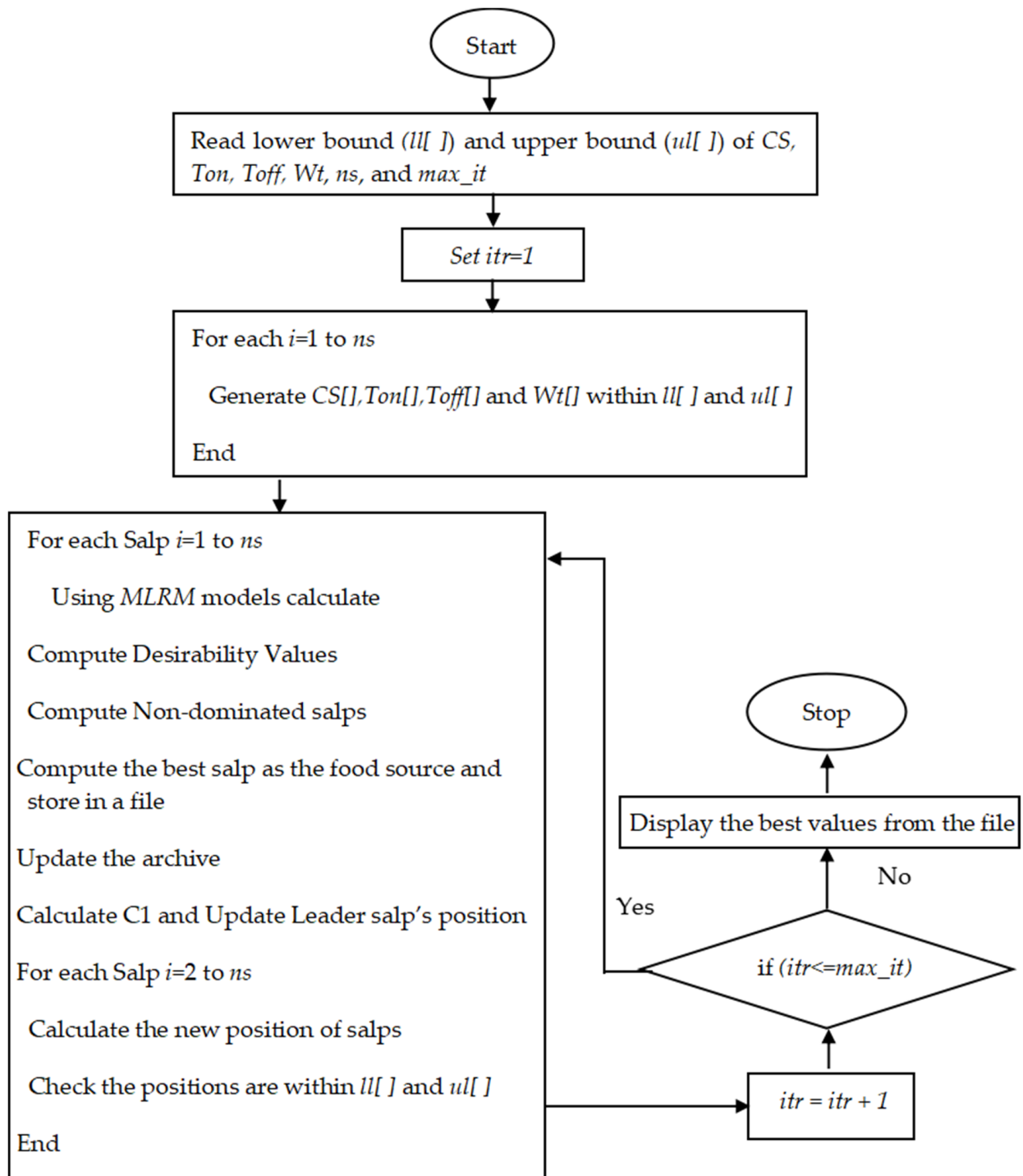


Figure 6. Flow Chart for SSO-DF algorithm.

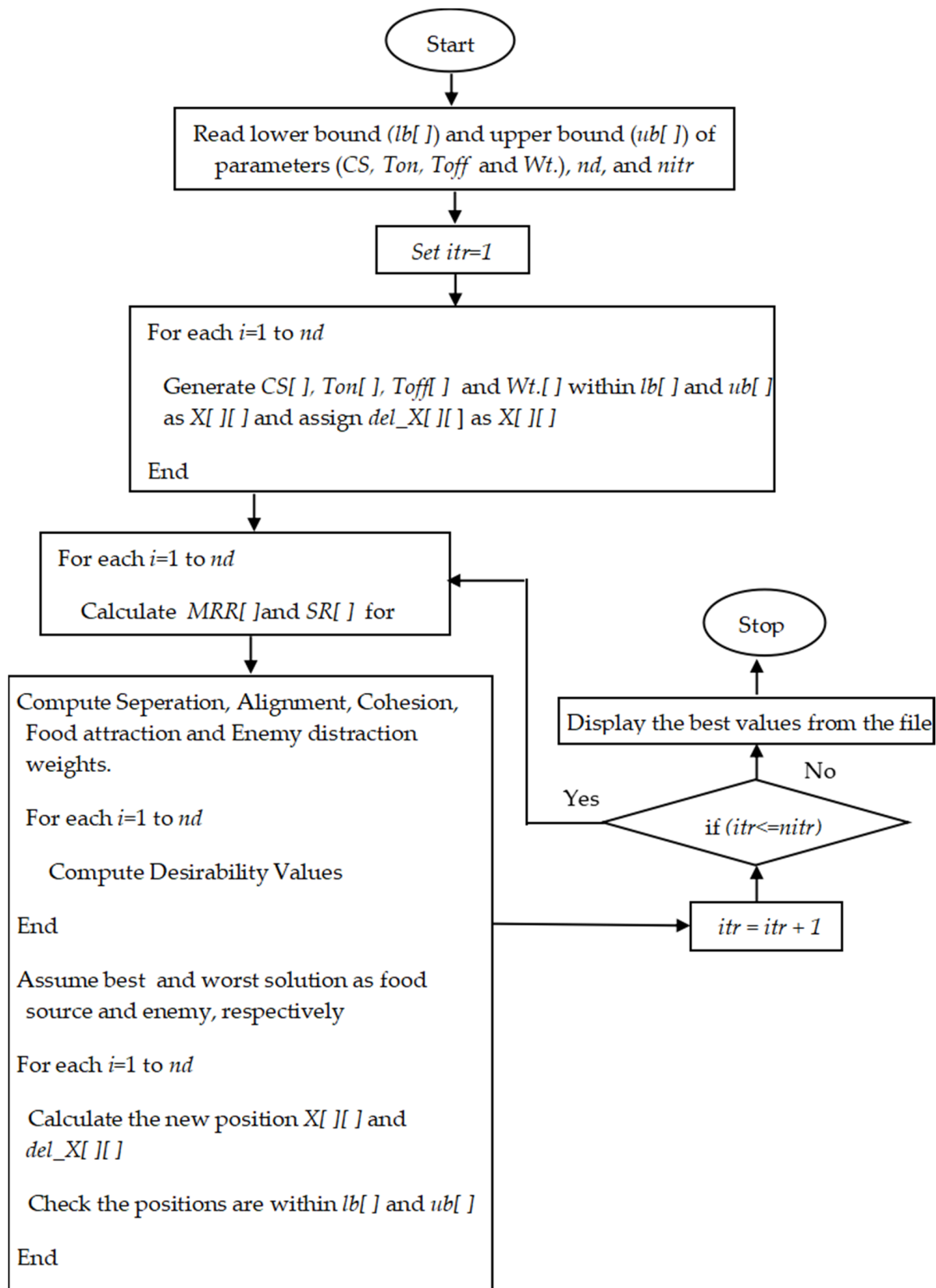


Figure 7. Flow Chart for DFO-DF algorithm.

3. Results and Discussion

3.1. Significance of Experimental Parameters on MRR and SR

Figures 8–10 exemplify the influence of the experimental control variables along with fractions of magnesite particulates, i.e., WM, LCM and DBM, on material removal rate surface roughness. The (*) symbol between the parameters in the contour plots denotes the interaction effect of two parameters on the responses while other parameters are held constant at central values. Black dots indicate the intersecting points of two process variables on the response surface curves. For all pulse-on time values, there is no discernible increase in MRR while cutting Al6061-Magnesite composites at cutting rates under 1.5 mm/min. However, a high MRR at a fast cutting speed of 2 mm/min is produced when the pulse-on time changes from 120 μ s to 125 μ s. This condition is practically the same for AA-LCM and AA-DBM composites.

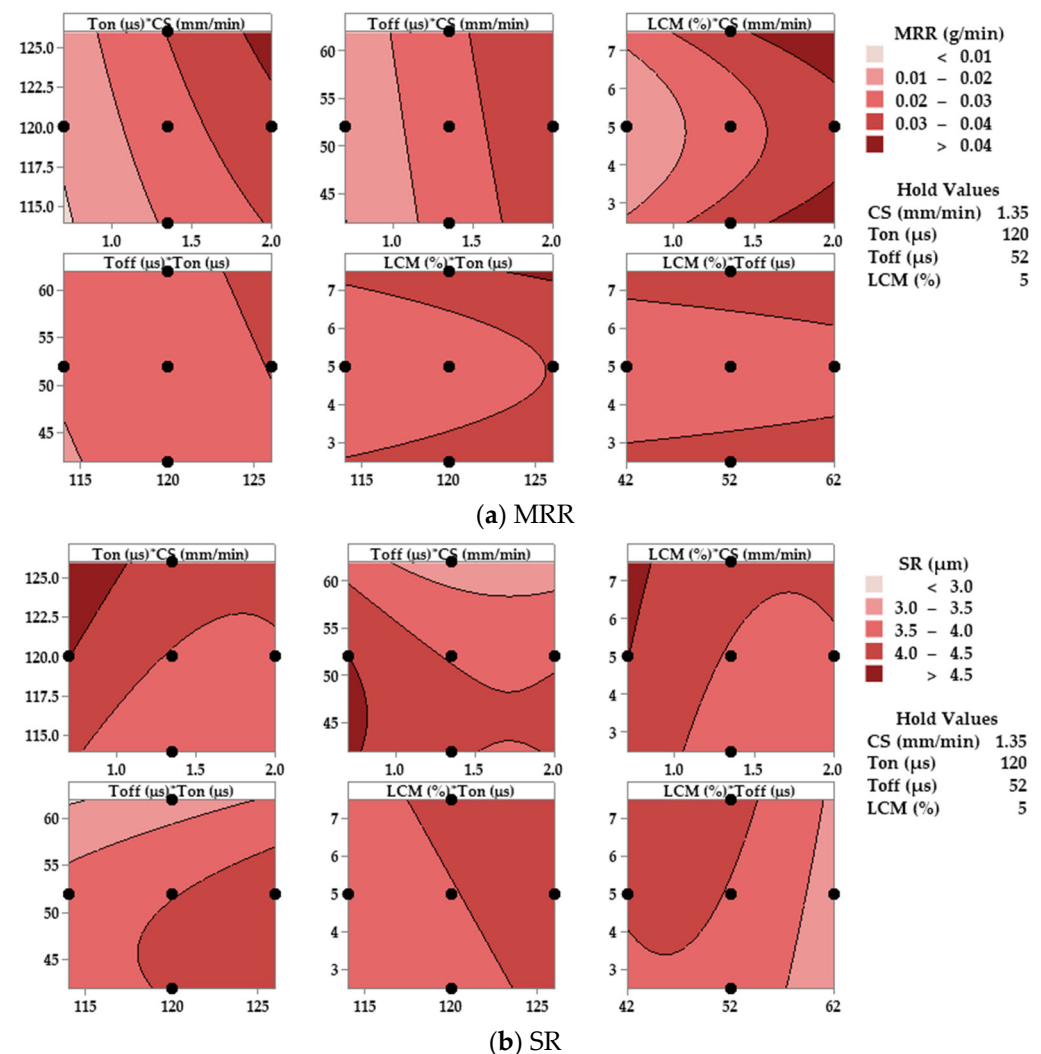


Figure 8. Contour Graph of Responses for AA-LCM (a) MRR (b) SR.

Spark-cutting energy is correlated with pulse duration [28]. More material melts at high sparking energy, and the crater size increases. Pulse-off time values, ranging from 55 μ s to 62 μ s, cause a significant shift in MRR when the cutting speed surpasses 1.7 mm/min. Based on observations, there is a little decrease in MRR at 4–6% of magnesite particles. But high cutting speeds make high MRR irrespective of the weight fractions of reinforcement. SR increases when the pulse-on times above 120 μ s at all cutting speeds. However, significant MRR is produced by high cutting speeds regardless of the weight fractions of reinforcement. At all cutting speeds, SR increases when pulse-on times exceed 120 μ s.

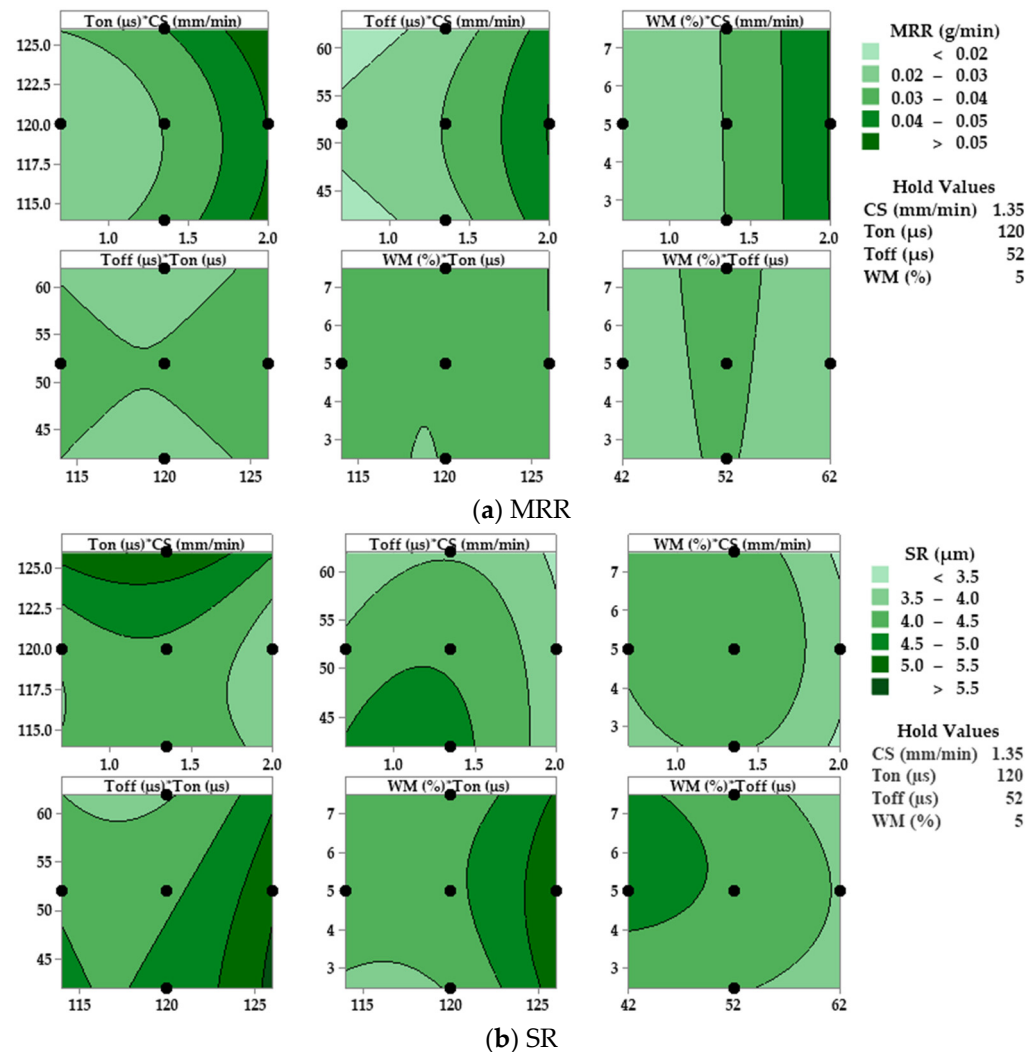


Figure 9. Contour Graph of Responses for AA-WM (a) MRR (b) SR.

Figures 11–13 show the FESEM images of the cut surfaces of the different grades of the composite. It has been observed that there are surface imperfections on the machined surfaces. This is mostly due to the recurrent melting and solidification of the alloy that is heated to high temperatures. But as these images demonstrate, there appears to be no difference in the surface morphology patterns on the machined surfaces with different proportions of magnesite particles. As the travelling wire passes over the molten pool, the surface gets distorted and the wear tracks are formed. The resultant high internal stresses and mismatch strain impact the microstructural properties of the composites [28]. When the alloy plastically deforms to accommodate the reduced volumetric expansion of the reinforcing particulates, a higher dislocation density is generated. With an increase in dislocation density, hardness and resistance to plastic deformation grow [29]. Excessive pulse-on times raise the potential for melting extra material, which increases MRR. Due to the quicker erosion of the specimen surface with longer pulse-on periods, the increased surface roughness leads to microcracks visible as shown in the FESEM images in Figures 11–13.

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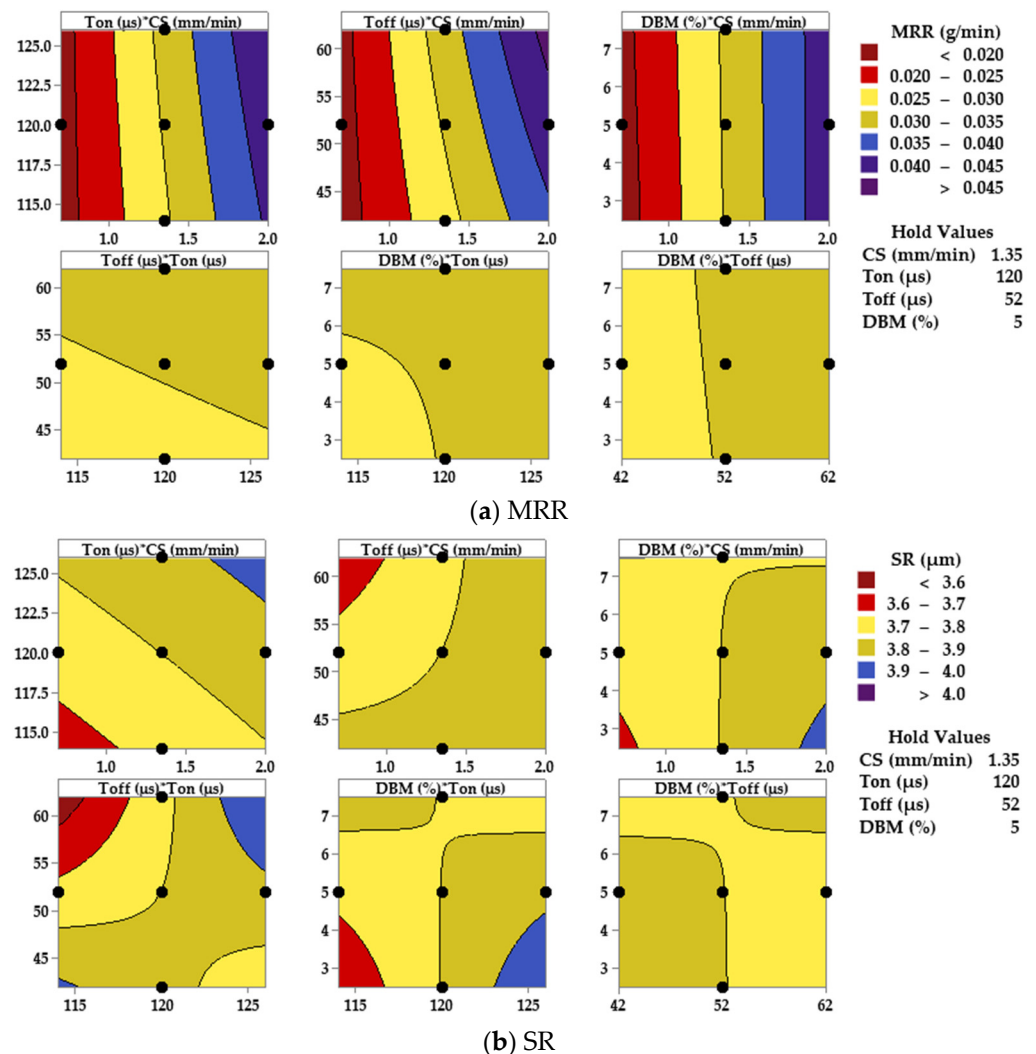
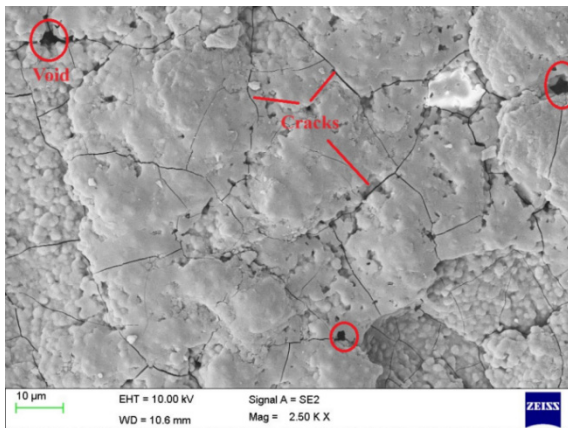


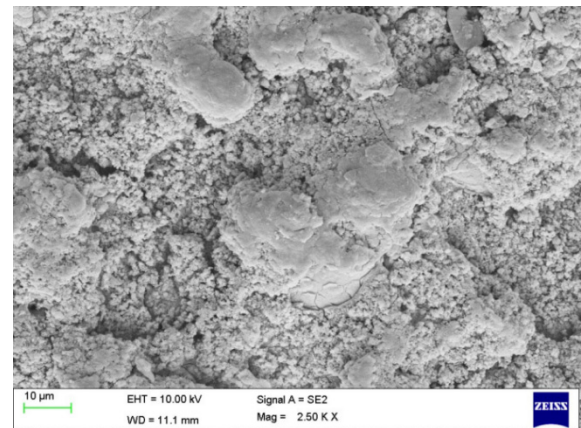
Figure 10. Contour Graph of Responses for AA-DBM (a) MRR (b) SR.

Figures 11–13 show the FESEM images of the cut surfaces of the different grades of the composite. It has been observed that there are surface imperfections on the machined surfaces. This is mostly due to the recurrent melting and solidification of the alloy that is heated to high temperatures. But as these images demonstrate, there appears to be no difference in the surface morphology patterns on the machined surfaces with different proportions of magnesite particles. As the travelling wire passes over the molten pool, the surface gets distorted and the wear tracks are formed. The resultant high internal stresses and mismatch strain impact the microstructural properties of the composites [28]. When the alloy plastically deforms to accommodate the reduced volumetric expansion of the reinforcing particulates, a higher dislocation density is generated. With an increase in dislocation density, hardness and resistance to plastic deformation grow [29]. Excessive pulse-on times raise the potential for melting extra material, which increases MRR. Due to the

quicker erosion of the specimen surface with longer pulse-on periods, the increased surface roughness leads to microcracks visible as shown in the FESEM images in Figures 11–13.

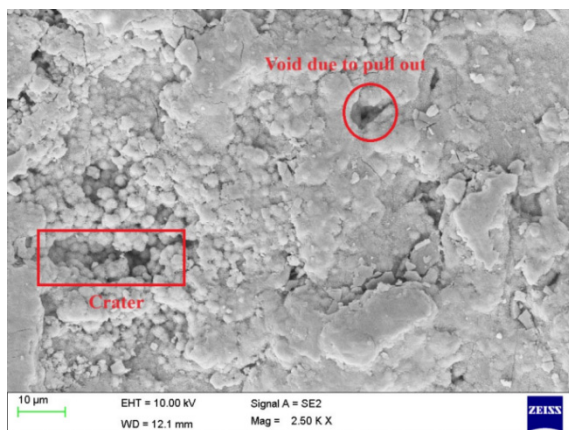


(a) AA-LCM2.5 at cutting speed = 2 mm/min, pulse-on time = 126 µs & pulse-off time = 62 µs

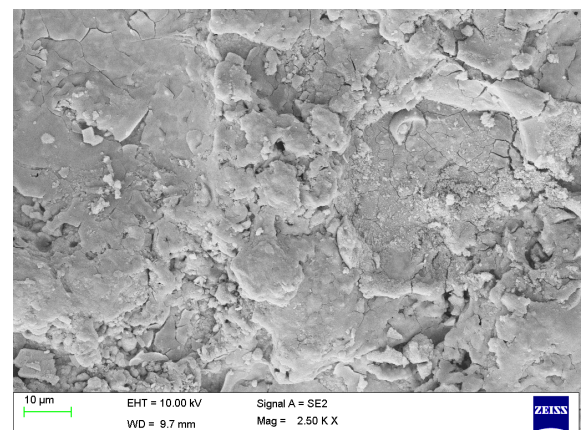


(b) AA-LCM5 at cutting speed = 1.35 mm/min, pulse-on time = 120 µs & pulse-off time = 42 µs

Figure 11. FESEM Image of the AA-LCM Specimen.

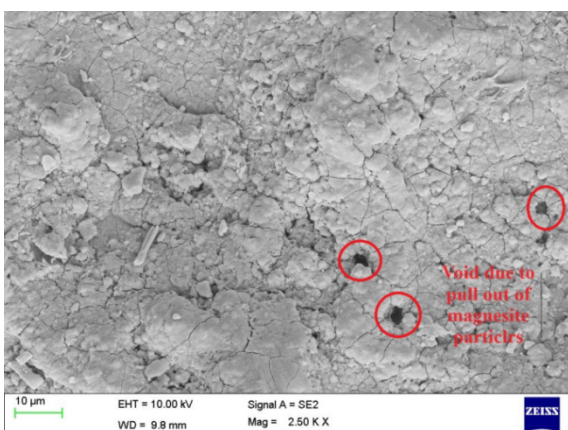


(a) AA-WM7.5 at cutting speed = 2 mm/min, pulse-on time = 126 µs & pulse-off time = 62 µs

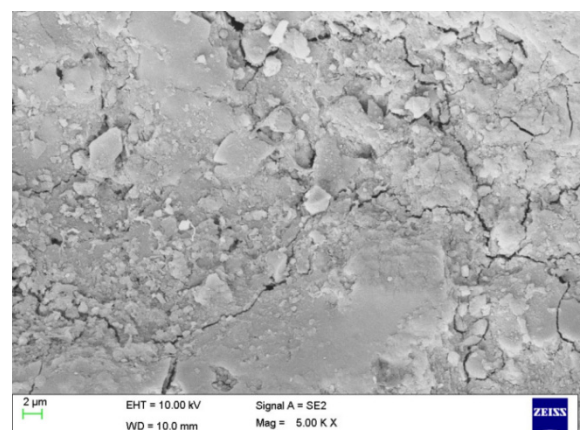


(b) AA-WM5 at cutting speed = 1.35 mm/min, pulse-off time = 120 µs & pulse-off time = 62 µs

Figure 12. FESEM Image of the Al6061-WM Specimen.



(a) AA-DBM2.5 at cutting speed = 2 mm/min, pulse-on time = 126 µs & pulse-off time = 62 µs



(b) AA-DBM7.5 at cutting speed = 0.7 mm/min, pulse-on time = 126 µs & pulse-off time = 62 µs

Figure 13. FESEM Image of the Al6061-DBM Specimen.

The surface morphology of the AA-WM7.5 composite specimens machined under WEDM variables of cutting speed of 2 mm/min, pulse-on time of 126 μ s, and pulse-off time of 62 μ s is shown in Figure 12a. The unreinforced matrix alloy has greater ductility than a magnesite reinforced alloy. Micro-voids form when magnesite particles alter the matrix's granular size and reduce its ductility [30]. The FESEM micrograph shows a crumpled layer as a result of the strong pulse current [31]. The sparse distribution of magnesite particles across the composite specimen is also noted. During machining, numerous magnesite particles on the surface become more pliable and detach. When pulse-on time increases, the machined workpiece's surface texture grows rougher. Long pulse-off periods create long chilling and flushing times, which tend to discharge more debris into the working gap and prevent the molten material from further solidifying on the machined surface [32]. High cutting speeds of around 2 mm/min make the surface harder irrespective of the variation in pulse on time. The WEDM produces good SR value for the AA-DBM composite at low T_{on} and high cutting speed. Due to their high hardness and ceramic properties, WM particles in the alloy matrix resist erosion at higher concentrations [33]. There is insufficient material removal at the pulse-on time of 42–62 μ s. At high cutting speeds and T_{on} , better surface quality was observed around 115–120 μ s. The cutting speed affects the surface quality when it is greater than 1.75 mm/min. However, even though other factors favour the surface quality, moderate cutting speed of 1.35 mm/min cause tiny fissures. To improve the surface quality throughout the WEDM process, lower T_{on} and greater T_{off} must be maintained [34]. WEDM finds it difficult to erode the hard ceramic particles in the composite specimen when the Wt. (%) of magnesite increases. Aluminium alloy tends to melt due to high-energy heating during machining, which minimizes surface fractures. Nonetheless, in the high-energy machining zone, the presence of magnesites decreases the heat conductivity of the aluminium alloy and encourages the production of microcracks.

3.2. Friedman Statistical Test

Figures 14–16 illustrates the convergence of the composite desirability by DFO-DF and SSO-DF algorithms for three case studies.

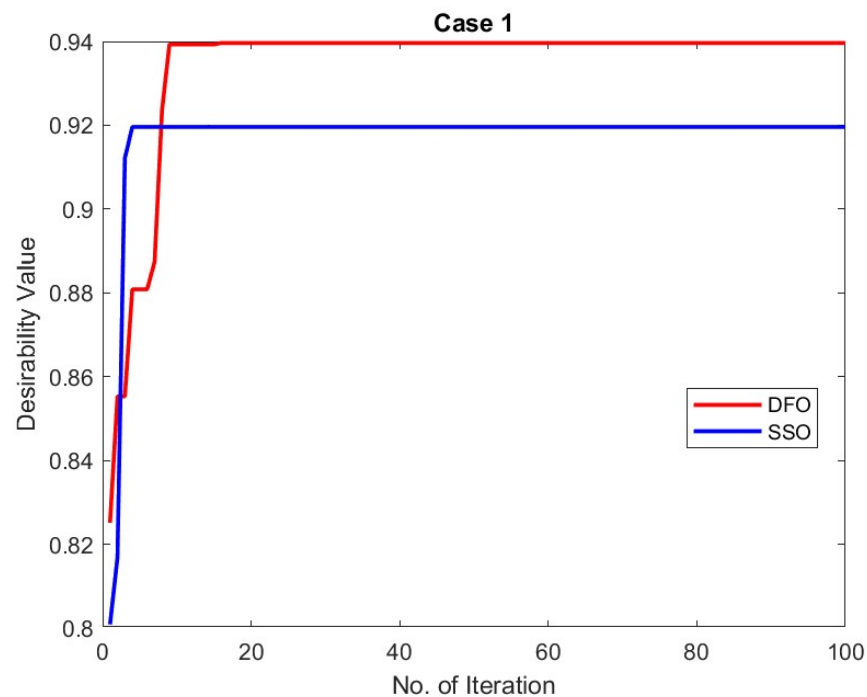


Figure 14. The convergence plot of composite desirability for WEDM of AA-WM composite.

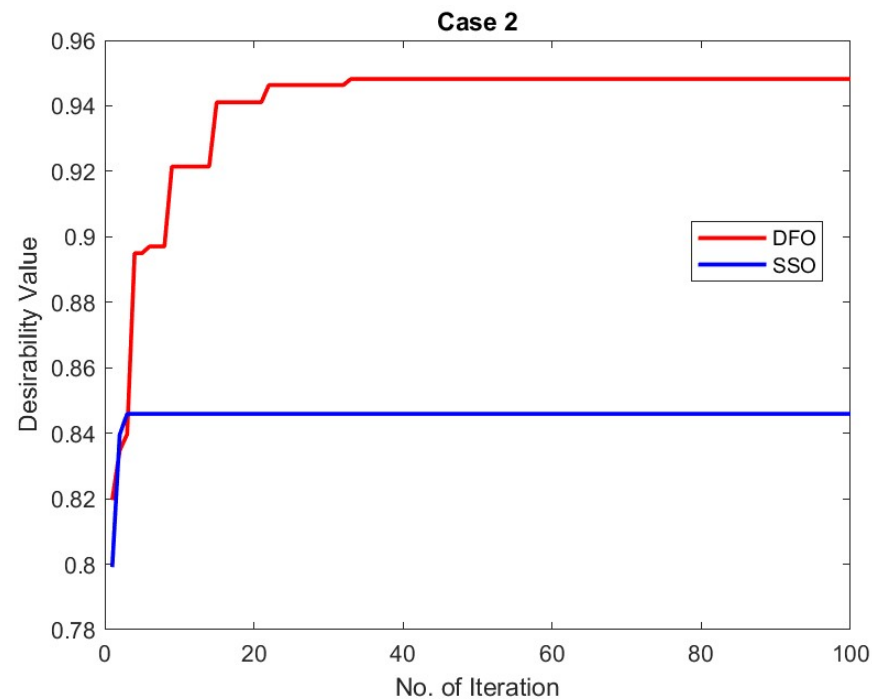


Figure 15. The convergence plot of composite desirability for WEDM of AA-LCM composite.

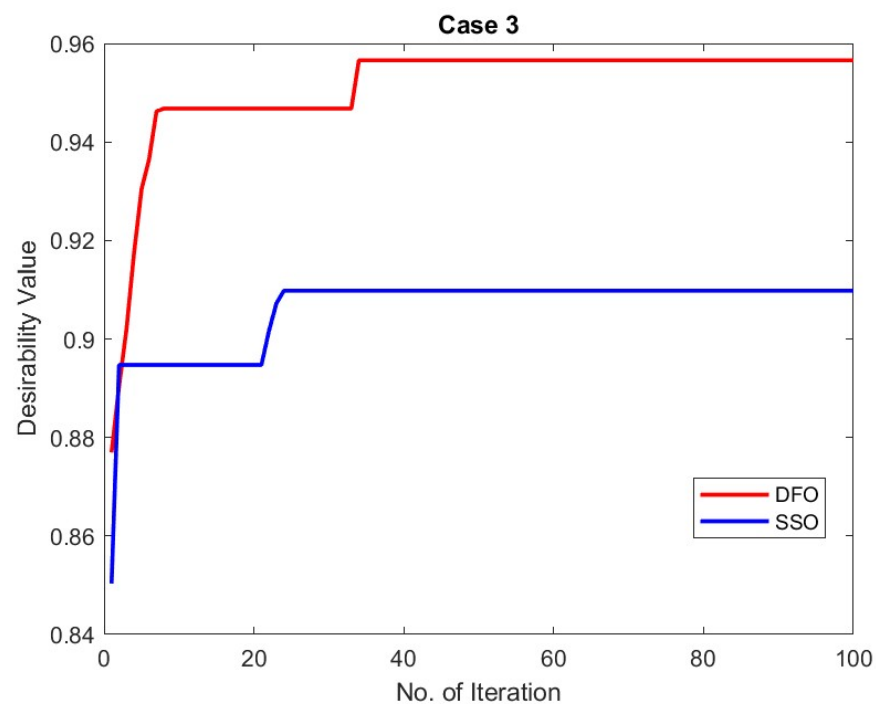


Figure 16. The convergence plot of composite desirability for WEDM of AA-DBM composite.

For both methods, the desirability function (DF) technique has been used to combine the dual objectives into a single objective. The results of the normality tests for 30 runs of each case are shown in Figure 17. The Friedman test, a nonparametric test, was employed to demonstrate the significant behavior of the SSO-DF and DFO-DF algorithms. A null hypothesis holds that the medians are equal.

Figure 17d presents the details of Friedman's test for the Analysis of Variance. All cases' probability values show that the null hypothesis was not accepted. Because the population of the algorithms is not equal in median value, the results generated by the algorithms differed greatly from one another. Table 10 displays the algorithms' Friedman's

mean rank value. It has been shown that the DFO-DF outperforms the SSO-DF method due to its higher mean rank value.

To assess the performance of the SSO-DF and DFO-DF algorithms, composite desirability (D) values generated by the RSM optimizer are also considered. The comparative bar chart of the RSM, SSO-DF, and DFO-DF algorithms is displayed in Figure 18. DFO-DF performs effectively for the multi-response optimization of the WEDM process. The optimization outcomes of the case studies are shown below.

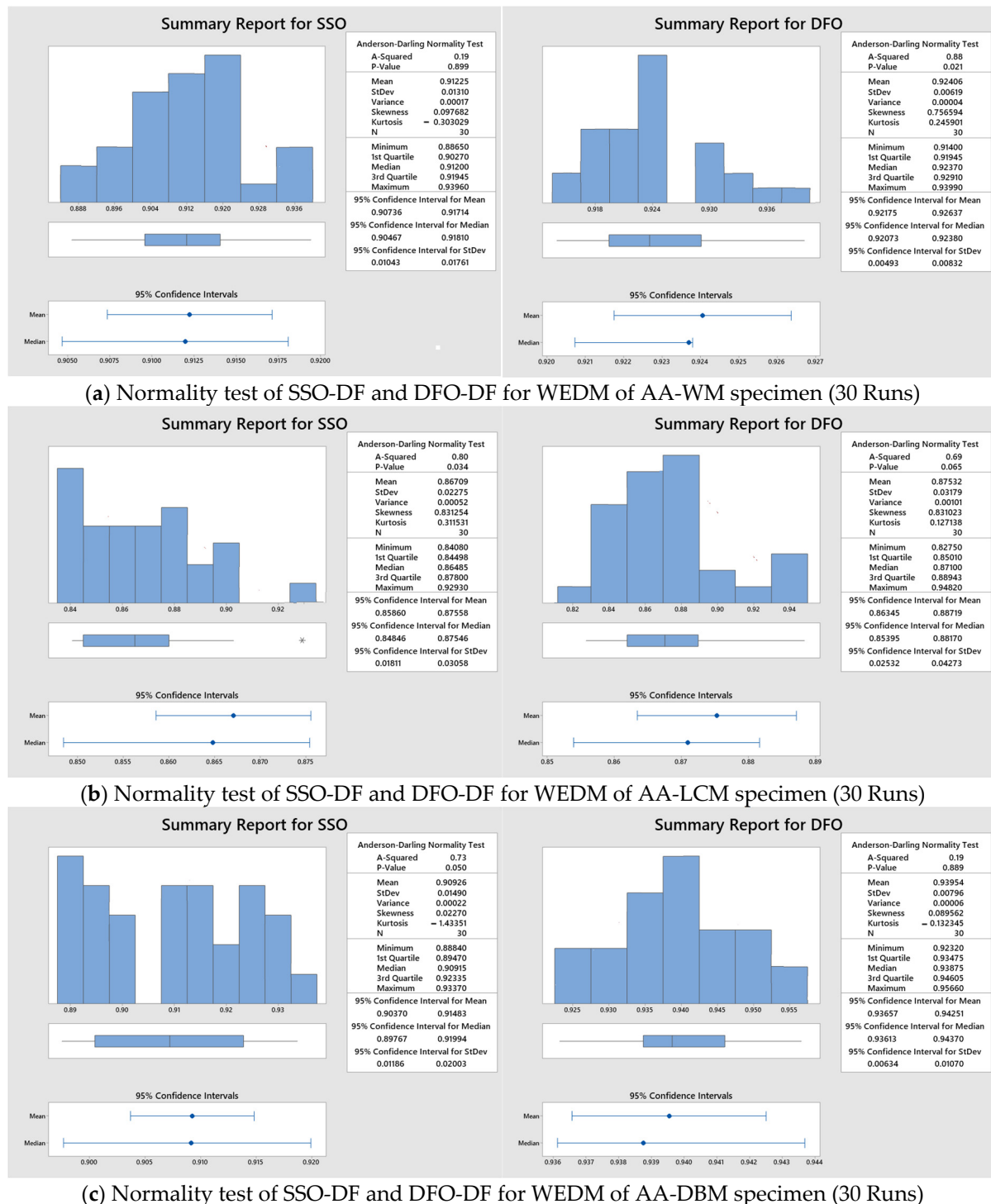


Figure 17. Cont.

Case #1					
Source	SS	DF	MS	Chi-Sq	Prob>Chi-Sq
Columns	8.06667	1	8.06667	16.13	0.000059
Error	6.93333	29	0.23908		
Total	15	59			
Case #2					
Source	SS	DF	MS	Chi-Sq	Prob>Chi-Sq
Columns	4.26667	1	4.26667	8.53	0.0035
Error	10.7333	29	0.37011		
Total	15	59			
Case #3					
Source	SS	DF	MS	Chi-Sq	Prob>Chi-Sq
Columns	11.2667	1	11.2667	22.53	0.00000207
Error	3.7333	29	0.1287		
Total	15	59			

(d) ANOVA results of Friedman's test

Figure 17. Normality test and ANOVA results of SSO-DF and DFO-DF (30 Runs).

Table 10. Optimum values by SSO-DF and DFO-DF algorithms.

Case	Algorithm	CS (mm/min)	T _{on} (μs)	T _{off} (μs)	Weight (%)	MRR (g/min)	SR (μm)	D	Mean Rank
#1	SSO-DF	2	114	52.4	2.50	0.056	3.358	0.94	1.133
	DFO-DF	2	114	48.2	2.52	0.055	3.346	0.94	1.867
#2	SSO-DF	2	126	62	2.50	0.043	3.180	0.93	1.233
	DFO-DF	2	126	62	2.50	0.043	3.180	0.948	1.767
#3	SSO-DF	2	114	62	4.98	0.052	3.263	0.934	1.067
	DFO-DF	2	114	62	5.18	0.052	3.275	0.957	1.933

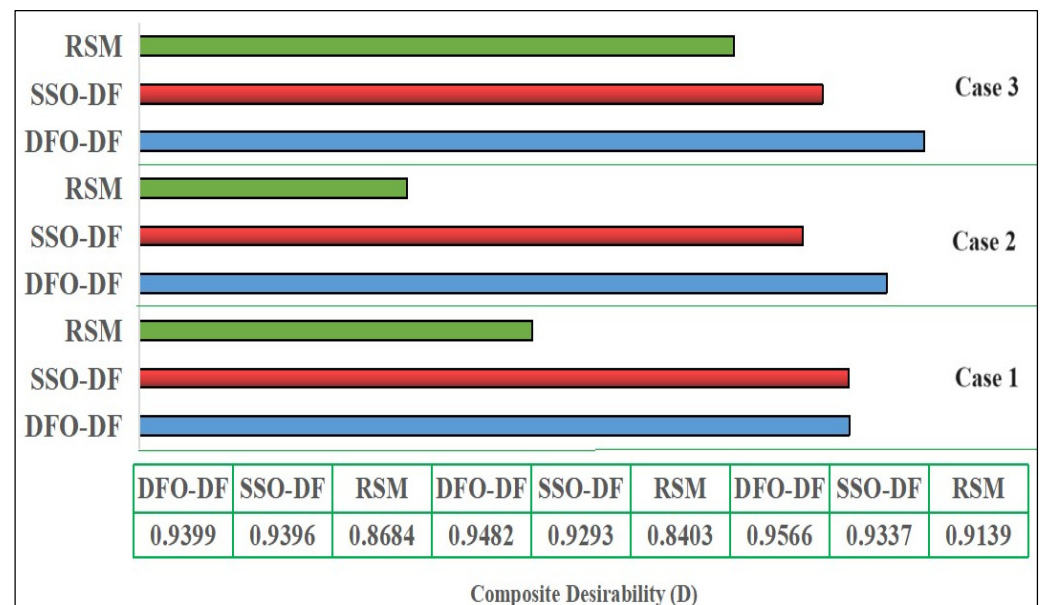


Figure 18. Comparison bar chart for composite desirability.

Case #1 Wire Electrical Discharge Machining of AA-WM: Cutting Speed = 2 mm/min, Pulse-on Time = 114 μs, Pulse-off Time = 48.23 μs, Wt. fractions of WM = 2.5192%, Material removal rate = 0.0552 g/min and Surface roughness = 3.3463 μm.

Case #2 Wire Electrical Discharge Machining of AA-LCM: Cutting Speed = 2 mm/min, Pulse-on Time = 126 μ s, Pulse-off Time = 62 μ s, Wt. fractions of LCM = 2.5%, Material removal rate = 0.0434 g/min and Surface roughness = 3.1802 μ m.

Case #3 Wire Electrical Discharge Machining of AA-DBM: Cutting Speed = 2 mm/min, Pulse-on Time = 114 μ s, Pulse-off Time = 62 μ s, Wt. fractions of LCM = 5.1833%, Material removal rate = 0.0524 g/min and Surface roughness = 3.2748 μ m.

The effectiveness of the DFO-DF algorithms is verified through confirmatory tests conducted under optimal machining settings. The results of the confirmation experiment are shown in Table 11.

Table 11. Confirmatory Experiment Results.

Case Study		Case #1	Case #2	Case #3
Optimized values by DFO-DF optimizer	MRR (g/min)	0.0552	0.0434	0.0524
	SR (μ m)	3.3463	3.1802	3.2748
Confirmatory experiment results	MRR (g/min)	0.056	0.044	0.053
	SR (μ m)	3.35	3.19	3.28
% of Error	MRR	1.45	1.38	1.15
	SR	0.11	0.31	0.16

It can be seen from all case studies that there is less than a 2% error between the projected response values and the experimental outcomes. WEDM ensures better performance for machining Al6061-Magnesite composites, based on optimization results.

4. Conclusions

This investigation examined the experimental features of the wire-electrical discharge machining of Al6061-Magnesite composites, following the central composite design (CCD). The optimal machining properties of AMMCs were found using algorithms such as SSO-DF and DFO-DF.

- The pulse-on time has a substantial impact on MRR. Longer pulse-on times enhance the prospect of more material melting, hence elevating MRR. Because the specimen's surface erodes and forms microcracks more quickly with longer pulse-on periods, the surface texture of the specimen becomes rougher.
- Magnesite granules are distributed sparingly throughout the specimen. Many of the magnesite particles become marginally more malleable during the machining process.
- WEDM generates low roughness on the specimen at low pulse-on time (114 μ s) and high cutting speed (mm/min). Microcracks start to occur on machined surfaces at higher pulse-on time values and increase the surface roughness.
- As the ceramic nature of higher concentrations of high-hardness magnesite particles resist erosion, microcracks are developed on the machined composite
- Performance models for the WEDM process have been developed that link process and product characteristics to performance metrics like MRR and SR.
- It was found that SSO-DF and DFO-DF, two meta-heuristic algorithms were very successful in identifying the optimum machining parameters.
- The WEDM parameters such as CS = 2 mm/min, T_{on} = 114 μ s, and T_{off} = 62 μ s produce the best results of MRR = 0.0434 g/min and SR = 3.18 μ m for Al6061/Wt. 2.5% LCM composite.
- Al6061/Wt. 2.5% WM has the best machinability among the other grades of waste magnesite composites based on the optimum WEDM conditions such as CS of 2 mm/min, T_{on} of 114 μ s, T_{off} of 48 μ s, MRR = 0.0524 g/min and SR = 3.275 μ m.
- The best machining parameters for Al6061/Wt. 5% DBM composite were determined to be CS = 2 mm/min, T_{on} = 114 μ s and T_{off} = 62 μ s, with MRR = 0.0524 g/min and SR = 3.275 μ m.
- The confirmatory trials established the appropriateness of these algorithms for optimizing the WEDM characteristics for Al6061-Magnesite composites.

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Nomenclature

WEDM	Wire Electrical Discharge Machining	RSM	Response Surface Methodology
AMMC	Aluminium Metal Matrix Composite	R^2	Coefficient of determination
LCM	Lightly-Calcined Magnesite	Y	Objective function
DBM	Dead Burnt Magnesite	a_0, b_i, c_i, d_i	Regression constants
WM	Waste Magnesite	P_i	i^{th} parameter's value
CCD	Central Composite Design	n_p	Number of parameters
MRR	Material Removal Rate (g/min)	i	Index value of parameters
SR	Surface Roughness (μm)	x_j^1	Position of lead Salp in the j^{th} variable
CS	Cutting Speed (mm/min)	F_j	Position of food in the j^{th} variable
T_{on}	Pulse-on Time (μs)	ub_j	Upper bound of the j^{th} variable
T_{off}	Pulse-off Time (μs)	lb_j	Lower bound of the j^{th} variable
FESEM	Field Emission Scanning Electron Microscope	c_1	Coefficient
EDAX	Energy Dispersive X-ray Analysis	c_2, c_3	Random numbers (0,1)
SSO	Salp-swarm Optimization	x_j^i	i^{th} follower-Salp in the j^{th} variable
DFO	Dragonfly Optimization	S_i	Separation behaviour of the i^{th} dragonfly
DF	Desirability Function	X	Position of the current dragonfly
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution	X_j	Position of the j^{th} neighbouring dragonfly
GRA	Grey Relational Analysis	A_i	Alignment behaviour by i^{th} dragonfly
PSI	Preference Selection Index	V_j	Velocity of the neighbour dragonflies
GA	Genetic Algorithm	N	Number of neighbours in the vicinity
PSO	Particle Swarm Optimization	C_i	Cohesion factor of the i^{th} dragonfly
HS	Harmony Search	F_i	Food source (i^{th} dragonfly)
SSO-DF	Salp-swarm Optimization-Desirability Function	X^+	Position of food source
DFO-DF	Dragonfly Optimization-Desirability Function	E_i	Position of foe of i^{th} dragonfly
AA-LCM	Aluminium 6061-Lightly-Calcined Magnesite	X^-	Position of foe
AA-DBM	Aluminium 6061-Dead Burnt Magnesite	ΔX	Step vector
AA-WM	Aluminium 6061-Waste Magnesite	ΔX_{t+1}	Step vector update
ANOVA	Analysis of Variance	s, a, c	Separation, Alignment, Cohesion factors
		f, e, w	Food, Enemy, Inertia factors
		t	Current iteration
		$d(\text{MRR})$	Individual desirability for MRR
		$d(\text{SR})$	Individual desirability for SR
		D	Composite desirability

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