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Hybrid optimization approach on electrical discharge machining process for hybrid Al-Al_2O_3/B_4C composites

P.K. Gupta, M.K. Gupta✉

Department of Mechanical Engineering, Motilal Nehru National Institute of Technology Allahabad, Prayagraj-211004, Uttar Pradesh, India

✉ mnnit.manoj@gmail.com, mkgupta@mnnit.ac.in

Abstract. In the present investigation, influences of process parameters such as pulse current, pulse on time, gap voltage, and sample compositions on the machining of hybrid Al-Al_2O_3/ B_4C composites through wire electrical discharge machining (WEDM) are carried out. The parameters were optimized to minimize both material removal rate (MRR) and surface roughness (SR) through Taguchi and Grey relational analysis. The hybrid Al-Al_2O_3/ B_4C MMCs containing the micro-particles of Al_2O_3 (purity 99 % and 100-325 mesh size) and B_4C (purity 99% and 400 mesh size) were prepared by stir casting with varying proportions (i.e. 100/0, 75/25, 50/50, 25/75 and 0/100) of Al_2O_3 and B_4C as a reinforcements. The morphology of the machined samples was also examined through SEM and found the presence of micro-ridges, micro craters, micro-cracks, black patches, debris, and micro-voids. The experimental results revealed the optimal grouping of process parameters as sample composition of B75A25 (75% B_4C +25% Al_2O_3), pulse on time of 32 μs, pulse current of 2 A, and gap voltage of 40 V.
Keywords: hybrid composites, metal matrix composites, optimization, wire electrical discharge machining, scanning electron microscopy

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1. Introduction

Apart from many advantages (i.e. high strength to weight ratio, higher transverse stiffness and strength, no water absorption, and good elevated temperature resistance) and many applications (i.e. automotive, aerospace, and structural) of single reinforced metal matrix composites (MMCs), they have some limitations also [1,2]. These limitations may be overcome using hybrid metal matrix composites (HMMCs). HMMCs can be prepared by reinforcing two or more types of ceramic particles or synthesis fibres in the metal matrix [3]. HMMCs are being considered in various fields due to their enhanced properties over single reinforced composites. These can be proffered for numerous engineering applications like automobile, marine, aerospace, structural, and mineral processing because of the improved specific strength, wear resistance, and thermal properties [4].

For utilization of synthesized MMCs, they are subjected to various cutting actions with conventional and non-conventional machining processes. During machining of MMCs by conventional processes, high temperatures are generated which leads to deformation of the cutting tools and worsen the product quality, also increasing the fabrication cost. Therefore non-conventional machining comes into the picture for the machining of these typical materials. The employ of non-conventional machining methods can enhance product quality and lessen the production costs for such materials. Among the existing non-conventional machining processes, WEDM is commonly accepted to fabricate complex profiles in composite materials [5].

WEDM is an electro thermal machining process that uses a moving conductive wire as an electrode to obtain the desired shape. In WEDM process, the selection of proper cutting parameters is an important task to avoid less MRR and poor surface finish due to wire breakage and short-circuiting [6]. Several researchers have reported their studies on MRR and SR of MMCs and HMMCS using WEDM. Kumar et al. [7] worked on optimization of WEDM for aluminium-based composites through GRA and reported optimum conditions as: peak current = 12A, pulse on time = 100 microseconds, wire feed rate = 6 m/min and wt.% of B_4C = 5. Goyal et al. [8] observed that the pulse on time and peak current are found to be the most significant factors towards MRR for Ni49Ti51 shape memory alloy. Kumar et al. [9] reported the optimum machining conditions for Al-SiC-B_4C composites as current = 20 A, pulse on time = 108.6 microseconds, wire feed rate = 10 mm/min, and 5.65% of the B4C content in the composites. Prasad et al. [10] also investigated the machining behaviour of Ti alloy through WEDM process. Karabulut et al. [11] found that the surface finish of AA6061-B_4C composite was predominantly affected by the peak current and voltage. Shayan et al. [12] also analyzed the influence of parameters on the performance of dry wire EDM for cemented tungsten carbide. Finally, EDM and WEDM machining processes are found to have better dimensional stability for high-strength temperature-resistant materials like MMCs and HMMCs [13-15]. Kanlayasiri and Boonmug [16] studied the machining of die steel through WEDM and observed that pulse on time and pulse peak current are the most influential factors for surface roughness. In another work, pulse on time and discharge current are found to be the most significant factors of surface roughness for Al- SiC MMCs [17]. Some other researchers' works based on the machining of MMCs and HMMCs are tabulated in Table1.

From the review of various literature, it was observed that very less works are carried out on the effect of reinforcement on the machinability of WEDM process. Further, no work is reported so far on the optimization of machining parameters for Al (6061)-Al_2O_3/B_4C through the hybrid GRA and Taguchi method. Therefore, the effect of variation in the proportion of Al_2O_3 and B_4C on MRR and SR of Al (6061)-Al_2O_3/B_4C and their optimization through the hybrid GRA and Taguchi method is performed.

2. Material and Manufacturing Process

Materials. The Al alloy (6061) is one of the most commonly used matrix materials for MMCs with chemical composition as provided in Table 2 [26]. To prepare the hybrid MMCs, Al alloy (6061) as matrix material and boron carbide (purity 99% and 400 mesh size (37μm)) and alumina (purity 99% and 100-325 mesh size (44-149μm)) as reinforcements were usedin the present work. All of the reinforcing and matrix materials were purchased from the local resources in Prayagraj, Uttar Pradesh, India.

Table 1. Review of hybrid metal matrix composite machined by electrical discharge machining

S.No.	Hybrid Composites	Electro-Discharge Machining				Ref.
		Parameters	Optimization Techniques	Optimized Values	Conclusions	
1.	$Al7075/Al_2O_3/SiC$	Pulse on time, Pulse off time, Pulse Current, Wire drum speed	Taguchi based GRA	Pulse on time = 4 μ s, Pulse off time = 6 μ s, Pulse current = 2A, Wire drum speed = 4m/min	• The surface roughness was increased with high discharge energy in spark and drum speed • Kerf width was improved with increasing drum speed due to the creation of large size cavities, voids and particles pull out	[18]
2.	Al6061/SiC/Graphite	Current, Pulse on time, Voltage, Flushing pressure	Least square techniques and ANOVA	-	Tool wear rate was increased with an increasing current and voltage but it decreased with increasing pulse on time and flushing pressure	[15]
3.	Al6063/SiC/Graphite	Voltage, Pulse current, Pulse off time, Pulse on time	Taguchi based GRA	Voltage = 60V, Pulse current = 32A, pulse on time = 4 μ s	The material removal rate and surface roughness were increased due to more energetic pulses because of the higher cavity formation	[19]
4.	$Al6351/SiC/B_4C$	Current, Pulse on time, Pulse duty factor, Gap voltage	ANOVA	The responses were influenced by pulse current with a contribution of 33.08% to electrode wear ratio, 76.65% to surface roughness, 48.08% to the power consumed	The machined surfaces contained craters, recast layers, surface waviness, and also the formation of bubbles	[20]

5.	AlSi10Mg/Graphite/Al_2O_3	Peak current, Flushing pressure, Pulse on time	ANOVA	Peak current with a contribution of 69.18% to surface roughness, Flushing pressure 43.26% contribution on MRR, Pulse on time 34.38% contribution on TWR	The surface roughness was increased with an increase in the flushing pressure due to the accumulation of alumina particles	[21]
6.	Al/B_4C/Graphite	Wire speed, Pulse on time, Pulse off time	Taguchi, RSM, ANOVA	Wire speed = 50m/min, Pulse on time= 5 μ s, Pulse off time =7 μ s	The MRR and SR were increased with the increase of wire speed and pulse-on time	[22]
7.	Al413/Fly ash/B_4C	Gap voltage, Pulse on time, Pulse off time, wire feed, reinforcement %	Taguchi, ANOVA	Gap voltage = 50V, Pulse on time =1 μ s, Pulse off time =10 μ s, Wire feed = 8m/min, Reinforcement = 6 %	The optimal predicted values were found for surface roughness and material removal rate 3.37 μ m and 13.0 mm^3/min respectively	[23]
8.	Al/SiC/B_4C	Peak current, Pulse on time, wire feed rate, B_4C content %, Pulse off time	Response surface methodology	Peak current = 20A, Pulse on time = 108.6 μ s, Wire feed rate = 10mm/min, B_4C content % = 5.65	The lower material removal rate was obtained in case of a lower wire feed rate due to lower heat energy strikes on the composite surfaces	[9]
9.	AZ31/Graphene/SiC	Reinforcement %, Doping %, Pulse on time, Pulse off time, Wire feed rate	Taguchi coupled GRA	Reinforcement = 0.2%, Doping = 10%, Pulse on time = 40 μ s, Pulse off time = 23 μ s, Wire feed rate = 2m/min	The variation in the thermal behaviour of reinforcements and matrix material affected the material removal rate	[24]
10.	Al6061/SiC/Graphite/Iron Oxide	Pulse peak current, Pulse on time, Pulse off time, Wire feed rate, Wire tension, Spark gap set voltage	ANOVA, Regression analysis	The improvement in MRR and Spark gap width by 33.72% and -27.28%	The size of craters formed on the machined surfaces affected by peak current and pulse on time	[25]

Table 2. Chemical composition of 6061Al alloy (wt.%)

Mg	Si	Cu	Cr	Fe	Al
0.92	0.57	0.21	0.12	0.09	Balance

Fabrication of composites. The flow chart diagram for fabrication of hybrid Al-Al_2O_3 /B_4C composite is shown in Fig. 1. In Figure 1, firstly, an ingot of Al alloy (6061) was converted into small pieces and then poured into a graphite crucible for smooth melting through an electric coil furnace at a temperature of 750°C. Subsequently, the crucible and Al_2O_3 and B_4C particles were preheated at a temperature of 400°C. Thereafter, preheated powders of reinforcements were mixed at a rotation of 600 *rpm* by employing a stirrer in two consecutive steps of 3 wt. % of reinforcement each for half of 10 min. A drop in temperature of around 15-20°C was seen during the mixing process. The degasser (flux material) was used to throw away the trapped gases and maintain the temperature of the mixture constant. After all, the mixture of Al_2O_3 and B_4C particles into molten Al alloy was poured into a die of cast iron for the production of specimens.

Methodology. The developed composite materials were machined through wire electrode discharge machining with the help of the high-power servo stabilizer. A wire of molybdenum with a 0.25 mm diameter was used as a tool material to perform the experiments. The cutting length of 30 mm was kept constant for all the composites. The experimental details are provided in Table 3. The experiments were conducted with various input parameters such as sample compositions, gap voltage (V), pulse on time (μs), and pulse current (A) with an objective to minimize both MRR and SR. The following input parameters for the WEDM are given in Table 4.

Fig. 1. Flow chart diagram for fabrication of hybrid metal matrix composites

Table 3. Experimental details for wire electrical discharge machining of hybrid metal matrix composites

Experimental facility	Specifications
Workpiece	Hybrid Al-MMCs (A0B0, B100A0, A100B0, A75 B25, B75A25, and B50A50
Machine	Wire electrical discharge machine (Ex 4032, Medha enterprises Kanpur)
Electrode	Molybdenum wire (0.25mm diameter)
Machining parameters	Sample composition (0/0, 100/0, 0/100, 25/75, 75/25, and 50/50),Gap voltage (40V, 44V, and 48 V), Pulse on time (32 µs, 64 µs, 128 µs), and Pulse current (2A, 3A , 4A)
Surface roughness measuring device	Surface roughness tester, and Make: Mitutoyo, Model: SJ-410

Table 4. The input process parameters for wire electrical discharge machining of hybrid metal matrix composites

Input process parameters	Level					
	1	2	3	4	5	6
Sample compositions	M1 (A0B0)	M2 (B100A0)	M3 (A100B0)	M4 (A75B25)	M5 (B75A25)	M6 (B50A50)
Gap voltage (V)	40	44	48	-	-	-
Pulse on time (µs)	32	64	128	-	-	-
Pulse current (A)	2	3	4	-	-	-

Table 5. Experimental results of material removal rate and surface roughness hybrid metal matrix composites

S. No	Sample Composition	Gap voltage (V)	Pulse on time (µs)	Pulse current (A)	MRR (cm^3/min)	SR (µm)
1	1	1	1	1	0.0252	3.0290
2	1	2	2	2	0.0222	3.2770
3	1	3	3	3	0.0190	3.6830
4	2	1	1	2	0.0102	1.3230
5	2	2	2	3	0.0141	1.7740
6	2	3	3	1	0.0174	1.9390
7	3	1	2	1	0.0208	2.7580
8	3	2	3	2	0.0207	2.7890
9	3	3	1	3	0.0247	2.6770
10	4	1	3	3	0.0186	2.4850
11	4	2	1	3	0.0248	2.5780
12	4	3	2	1	0.0209	2.7840
13	5	1	2	2	0.0244	2.0260
14	5	2	3	3	0.0206	2.2390
15	5	3	1	1	0.0186	2.2170
16	6	1	3	2	0.0185	2.6200
17	6	2	1	2	0.0245	2.4600
18	6	3	2	3	0.0207	2.3110

The experiments were designed by Taguchi method and $L18$ array was used for conducting the experiments. The experimental results are shown in Table 5. The MRR was computed by taking weight differences of before and after workpiece machining per minute. It was computed by the following formula.

$$MRR = \frac{W_i - W_f}{\rho t}, \quad (1)$$

where W_i and W_f are weigh of the specimens before and after machining, ρ – density of the specimens and t – period of machining (minute).

The surface roughness of the machined area or section was measured through a profile meter (Mitutoyo-Model SJ-410) with a traverse length and speed of 5 mm and 0.25 mm/s respectively.

3. Results and discussion

Design of experiment (DOE). The design of the experiment is utilized for minimizing the number of experiments that can be done by Taguchi method. Minitab 17 software was used for designing the experiments as per requirements. Four input parameters with one of them having six levels and others having three levels were used as tabulated in Table 4. $L18$ array was used in this work and resultes are tabulated in Table 5.

Analysis of output/response parameters. The signal-to-noise ratio (S/N) was taken into account for analyzing the input parameter over the output response. The outputs/responses such as MRR and SR, both are the minimizing criteria of characteristics. So, smaller values of MRR and SR are set as better characteristics. The S/N can be found by the below equation (2).

$$\frac{S}{N} = -10\log_{10}[\frac{1}{n}\sum(y_{ij}2)], \quad (2)$$

where, n – no of observations, y_{ij} – observed response, $i = 1,2\ldots n$, $j = 1,2\ldots k$.

Table 6. Signal to noise ratio (S/N) and normalized values for hybrid metal matrix composites

S. No	S/N ratio (MRR)	S/N ratio (SR)	Normalized value (MRR)	Normalized value (SR)
1	31.9720	-9.6260	1	0.2771
2	33.0729	-10.3095	0.7987	0.1720
3	34.4249	-11.3240	0.5874	0.0000
4	39.8280	-2.4312	0	1.0000
5	37.0156	-4.9791	0.2575	0.8089
6	35.1890	-5.7516	0.4758	0.7390
7	33.6387	-8.8119	0.70481	0.3919
8	33.6806	-8.9090	0.6964	0.3788
9	32.1461	-8.5530	0.9644	0.4263
10	34.6097	-7.9065	0.5558	0.5076
11	32.1110	-8.8934	0.9689	0.4682
12	33.5971	-6.1328	0.7111	0.3809
13	32.2522	-7.0011	0.9466	0.7021
14	33.7227	-6.9153	0.6943	0.6119
15	34.6097	-8.3660	0.5603	0.6212
16	34.6566	-7.8187	0.5541	0.4504
17	32.2167	-7.2760	0.9519	0.5182
18	33.6806	-8.2760	0.6981	0.5814

Multi-response optimization using Grey Relational Analysis. Nowadays, multi-criteria decision-making (MCDM) techniques have received attention among researchers due to their absolute capacity to judge unique choices on various criteria for possible determination of the best. In this work, MCDM combined with grey relational analysis (GRA) and Taguchi method has been proposed to study the optimization problem for the wire electrode discharge process of Al alloy (6061) hybrid composites. The GRA is the multi-response optimization process contributing toward finding out the optimum combination of process parameters and the effect of each input parameter on the responses. The methodology consists of a number of steps as follows.

Step 1. Normalization. It is required to normalize the output responses before analyzing them with the grey relation theory and rated between 0 and 1. The normalization for output response such as MRR and SR can be done with the help of equation (3).

$$Z_{ij} = \frac{\max(y_{ij}, i = 1,2,3.........n) - y_{ij}}{\max(y_{ij}, i = 1,2,3.........n) - \min(y_{ij}, i = 1,2,3........n)}, \quad (3)$$

where y_{ij} is the J^{th} performance characteristics and $\min y_{ij}$ and $\max y_{ij}$ values of the J^{th} performance characteristics for the i^{th} experiments respectively.

The calculated SN ratio for individual response/output and its normalized value are given in Table 6.

Step 2. Calculation of Grey relational coefficient. The grey relational coefficients can be calculated from the generalized formula as shown in equation (4) and also, the characteristics coefficient is assumed to be $\xi = 0.5$.

$$(y_0(k), y_i(k)) = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{0j}(k) + \xi\Delta_{\max}}, \quad (4)$$

where i =1,2… n, k =1,2… m, n is the number of experimental data items and m is the number of responses, $y_0(k)$ is the reference sequence ($y_0(k)$ = 1, k =1,2… m), $y_i(k)$ is the specific comparison sequence, $\Delta_{0j} = \|y_0(k) - y_j(k)\|$ – the absolute value of the difference between $y_0(k)$ and $y_i(k)$, $\Delta_{\min} = \|y_0(k) - y_j(k)\|$ – the smallest value of $y_i(k)$, $\Delta_{\max} = \|y_0(k) - y_j(k)\|$ – the largest value of $y_i(k)$, ξ is the coefficient constant, which is defined in the range $0 \le \xi \le 1$.

Table 7. Deviation sequence and corresponding grey relational coefficient and grey relational grade for hybrid metal matrix composites

S. No	Deviation sequence (MRR)	Deviation sequence (SR)	GRC (MR)	GRC (SR)	GRG	RANKS
1	0	0.7229	1	0.40887	0.7044	6
2	0.2013	0.8280	0.7129	0.376516	0.5447	12
3	0.4126	1.0000	0.5479	0.333333	0.4406	18
4	1	0.0000	0.3333	1	0.6667	8
5	0.7425	0.1911	0.4024	0.7235	0.5629	11
6	0.5242	0.2610	0.4882	0.6570	0.5726	10
7	0.2952	0.6081	0.6288	0.4512	0.5400	14
8	0.3036	0.6212	0.6222	0.4459	0.5341	15
9	0.0356	0.5737	0.9335	0.4657	0.6996	7
10	0.4442	0.4924	0.5295	0.5038	0.5167	16
11	0.0311	0.5318	0.9415	0.4846	0.7131	4
12	0.2889	0.6191	0.6338	0.4468	0.5403	13
13	0.0534	0.2979	0.9035	0.6267	0.7651	1
14	0.3057	0.3881	0.6206	0.5629	0.5918	3
15	0.4397	0.3788	0.5321	0.5689	0.5505	2
16	0.4459	0.5496	0.5286	0.4764	0.5025	17
17	0.0480	0.4818	0.9124	0.5093	0.7108	5
18	0.3019	0.4186	0.6236	0.5443	0.5839	9

Calculation of Grey relational grade. The grey relation grade (GRG) for multi-objective responses can be found with the help of the grey relational coefficient of different responses for the MRR and SR. The evaluations of performance characteristics depend on the GRG values.

The following sequencing order of all the experiments is tabulated in Table 7. The grade which decided the rank of performance characteristics was obtained by using the equation (4).

$$\delta j = \frac{1}{k}\sum_{i=1}^{m} y_{ij}, \quad (4)$$

where δ_j – GRG for j^{th} experiment and k – number of performance characteristics.

Optimization techniques – Taguchi method. Based on GRG values, Taguchi optimization techniques are employed. The outcomes of this optimization were obtained as shown in Table 7. It is necessary to find out the effect of each parameter at different levels on the GRG. The obtained grey relational grade value for each level and corresponding average grade was presented in Table 7. Generally, the higher GRG value offers better output responses. The optimum condition can be found from response Table 8 (sample composition = B75A25 (75%B_4C +25% Al_2O_3), pulse on time (μs) = 32, pulse current (A) = 2, gap voltage (V) = 40). The sequence of input parameters that affect the multi-objective of minimum MRR and SR were sample composition followed by pulse on time, pulse current, and gap voltage.

Table 8. Response Table of grey relational grade for hybrid metal matrix composites

Level	Sample composition	Gap voltage (V)	Pulse on time (μs)	Pulse current (A)
1	0.5632	0.6159	0.6742	0.6176
2	0.6007	0.6096	0.5895	0.5565
3	0.5912	0.5646	0.5264	0.6160
4	0.5900			
5	0.6358			
6	0.5991			
Delta	0.0725	0.0513	0.1478	0.0612
Rank	2	4	1	3

Table 9. ANOVA results for hybrid metal matrix composites

Source	Degree of freedom	Sum of square	Mean square	Percentage Contribution
Sample code	5	0.008231	0.001646	3.08
Pulse on time (μs)	2	0.009391	0.004695	8.80
Pulse current(A)	2	0.066012	0.033006	61.83
Gap voltage (V)	2	0.014568	0.007284	13.65
Residual Error	6	0.040506	0.006751	12.65
Total	17			

Analysis of variance (ANOVA). It is the statistical method applied for finding the interaction between control factors utilized in the present experimental investigation. ANOVA was performed using Minitab version 17 software to find the contribution of each parameter for multi-objective responses. It is utilized to observe the interaction between the experimental parameters (sample code, pulse on time, pulse current, and gap voltage), and the results are presented in Table 9. The percentage contribution of process parameters for minimum MMR and SR was found using ANOVA as such: sample code (3.08%), pulse on time (8.80%), pulse current (61.83%), and gap voltage (13.65%). The main effect plot for grey relational grade value is shown in Fig. 2. From the main effects plot of the mean, it was found that the combination of optimal parameters and their levels was SC5GV1POT1PC1.

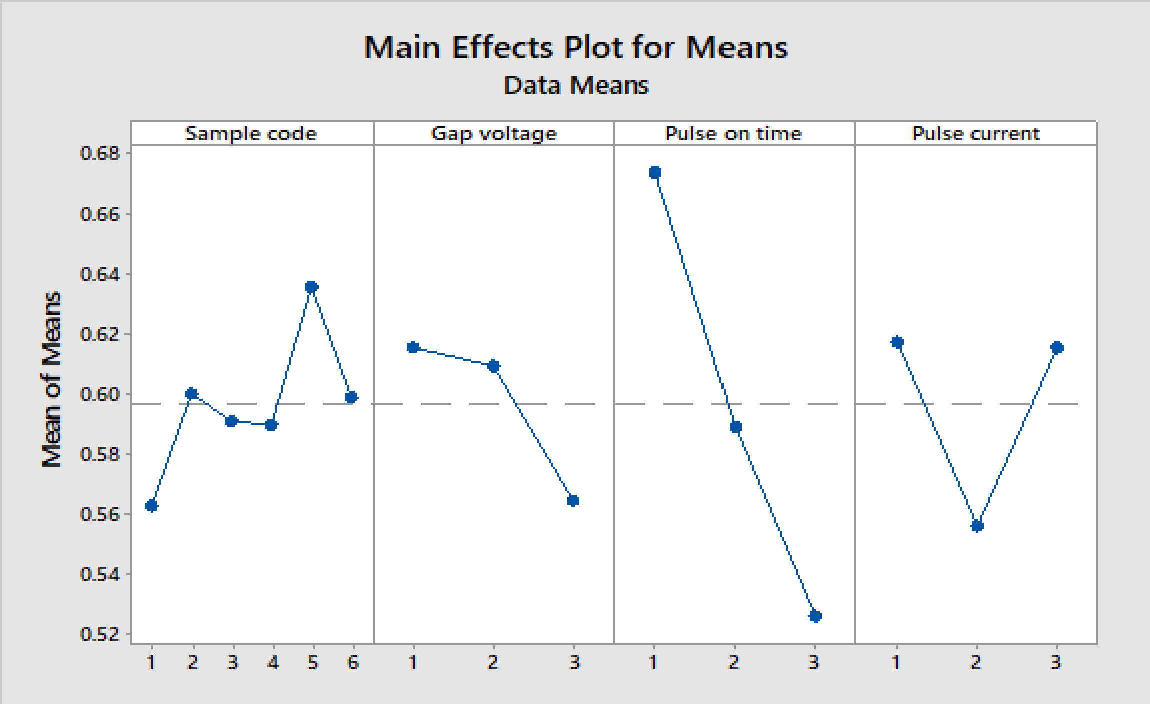

Fig. 2. Main effect plot of means for hybrid metal matrix composites (higher is better)

Confirmation tests. A confirmation experiment is performed to validate the hybrid approach of GRA and Taguchi implementation for optimization. The grouping of process parameters (Trial13) for which the quality characteristics yielded the peak value of grey relational grade (0.7651) was selected as the initial setting of the process parameter.

The responses received for the initial parameter setting were compared with the optimal parameter setting. It was observed that the hybrid approach of the GRA-Taguchi method had marginally improved the performance characteristics. From Table 10, an improvement in the performance is identified using the optimal condition in the WEDM process. The GRG is increased to 0.9886 from the initial parameter with a significant increase of 0.2235. Table 10 shows the confirmation test for the value of GRG for hybrid Al-Al_2O_3/B_4C composites.

Table 10. Confirmation test for hybrid metal matrix composites

Sources	Initial parameters	Optimum parameters	
		Prediction	Experimental
Combination of testing parameters	SC5GV1POT2PC2	SC5GV1POT1PC1	SC5GV1POT1PC1
Grey relational grade	0.7651	0.8283	0.9886
Improvement in grade		0.0632	0.2235

Parametric effect on the outputs/ responses

Material removal rate. The variations of MRR with a pulse on time at different pulse currents and voltage for hybrid metal matrix composites are shown in Fig. 3. It can be seen that the MRR of machined area for sample (A0B0) was higher in comparison to other composites such as B100A0, A100B0, A75B25, B75A25, and B50A50 due to its higher value of thermal conductivity (175W/m-K) that quickly conducts the discharge energy on its surface. Also, there were lower values of MRR for all the developed composites (B100A0, A100B0, A75B25, B75A25, and B50A50) than Al alloy matrix because of the non-conductive nature of reinforcing materials such as alumina and boron carbide that protect the surface of composite from discharge energy [9]. As the discharge energy is responsible for the machining of the Al alloy (6061) sample and composites.

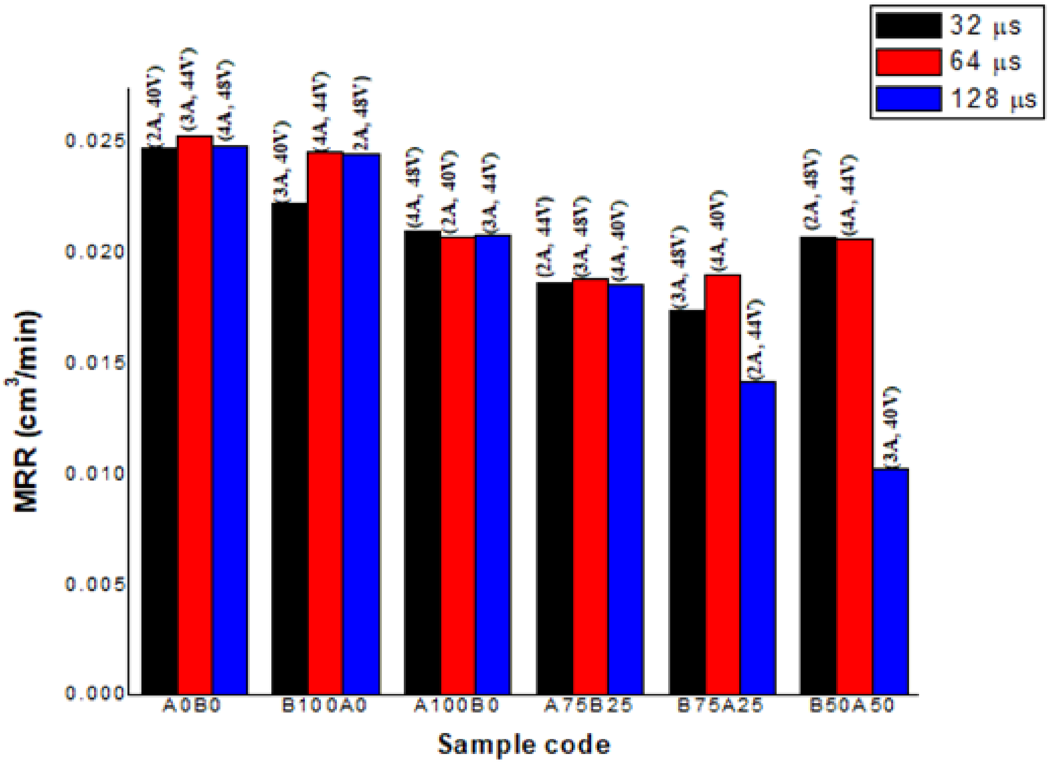

Fig. 3. Variations of material removal rate with a pulse on time at different pulse current and voltage for hybrid metal matrix composites

For sample A0B0, the MRR was increased with an increase in pulse on time from 32µs to 64µs due to the higher discharge energy available at the high value of gap voltage (44V) and pulse current (3A). The value of MRR was observed the lowest at the highest level of pulse on time (128µs) due to the welding phenomenon found in the molten pool of the Al alloy sample [8]. The composite sample B100A0 offered the higher MRR at a level of 64 µs pulse on time in comparison to pulse on time of 32µs due to more discharge strikes on the machined surface. The maximum MMR was seen at 64 µs of pulse on time for composite B100A0, whereas its lower value was seen at 128 µs pulse on time because of the rewelding phenomenon of molten metal. For sample A100B0, the lowest value of MRR was found at the level of pulse duration (64µs), pulse current (2A), and voltage gap (40V). A similar trend was found for the Al alloy sample.

For sample (A75B25), the MRR value was found to be increased with increasing the pulse duration from 32 µs to 64µs at a higher level of pulse current and gap voltage. Similar trends were found for the samples A0B0 and B100A0 as well. It was also found that the value of MRR was higher for sample B75A25 at a high value of pulse current (4A) and pulse duration (64 µs) for a given voltage due to discharge energy available for a prolonged time [7-9]. The lowest value of MRR for sample B75A25 was obtained at pulse on time 128 due to arcing of spark happened for machining conditions (2A, 44V). For the composite (B50A50), the MRR was decreased by decreasing the gap voltage for the prolonged pulse on time (64 µs). It happened due to the low spark energy on the machined surface. The lowest MRR was observed for sample B50A50 at a pulse duration of 128µs credited to the welding and arcing phenomenon. The lowest value of MRR for all the composites including Al alloy was found at machining conditions (128µs, 3A, and 40V). Radhika et al. (21) worked on the optimization of electrical discharge machining parameters of aluminium hybrid composites using the Taguchi method and they observed that peak current is a highly influential parameter on surface roughness followed by a pulse of time and flushing pressure. Arunkumar and Raghunath [27] found that the peak current and pulse on time influenced considerably the material removal rate for Mg/SiC composites.

Surface roughness. The variations of surface roughness at different machining conditions with a pulse on time for different composites are shown in Fig. 4. In comparison with Al alloy, the entire composite samples (B100A0, A100B0, A75B25, B75A25, and B50A50) have the lowest average surface roughness due to the addition of nonconductive reinforcing materials such as alumina and boron carbide that reduces the extent of spark or discharge energy on the surface[7,8]. Shayan et al. [12] found similar results during the machining of cemented tungsten carbide with the help of dry wire electro-discharge machining.

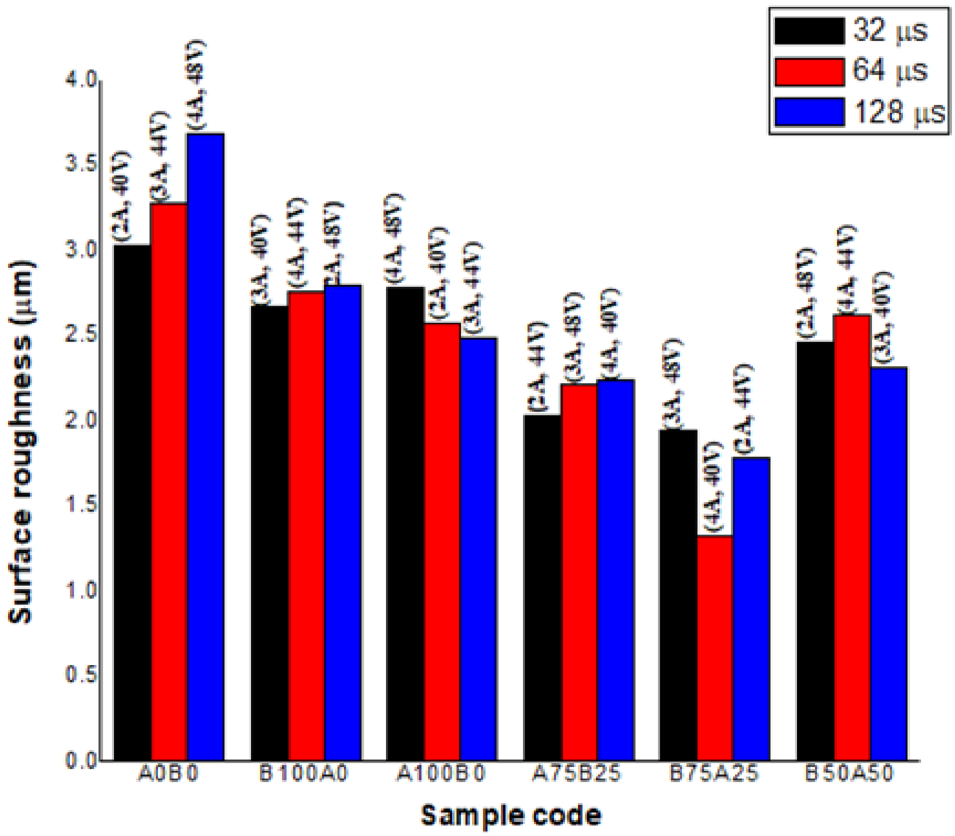

Fig. 4. Variations of surface roughness with a pulse on time at different pulse current and voltage for hybrid metal matrix composites

Generally, it is found that the extent of discharge or spark energy affects the surface characteristics. For sample A0B0, the SR was increased with an increasing pulse on time (32 µs to 128µs) due to the increased spark or discharge energy at all the machining conditions [16]. A similar trend was followed by the samples (B100A0) and A75B25. The sample A100B0 has a decreasing SR trend with increasing pulse on time (32 µs to 64µs) due to the decrease in gap voltage or intensity of pulse current. It was found that sample A100B0 had the lowest SR at machining conditions of 3A, 44V, and 128 μs due to the striations effect on the reinforcing particles [8].

Surface topography of the machined surface. Figure 5 shows the micrograph images of the WEDMed surface containing micro ridges, micro craters, micro-cracks, black patches, debris, and microvoids [13]. In Figure 5(a), more craters on the machined surface of monolithic aluminium alloy (A0B0) were observed. This happened due to matrix material removal because of the higher thermal conductivity of aluminium alloy 6061. The microvoids were observed due to the release of gases entrapped during machining and the electrochemical dissolution of the workpiece. In Figure 5(b), the micro-cracks were present near the particle-matrix interface because of debonding [28]. Similarly, micro craters were observed in the composite B100A0.

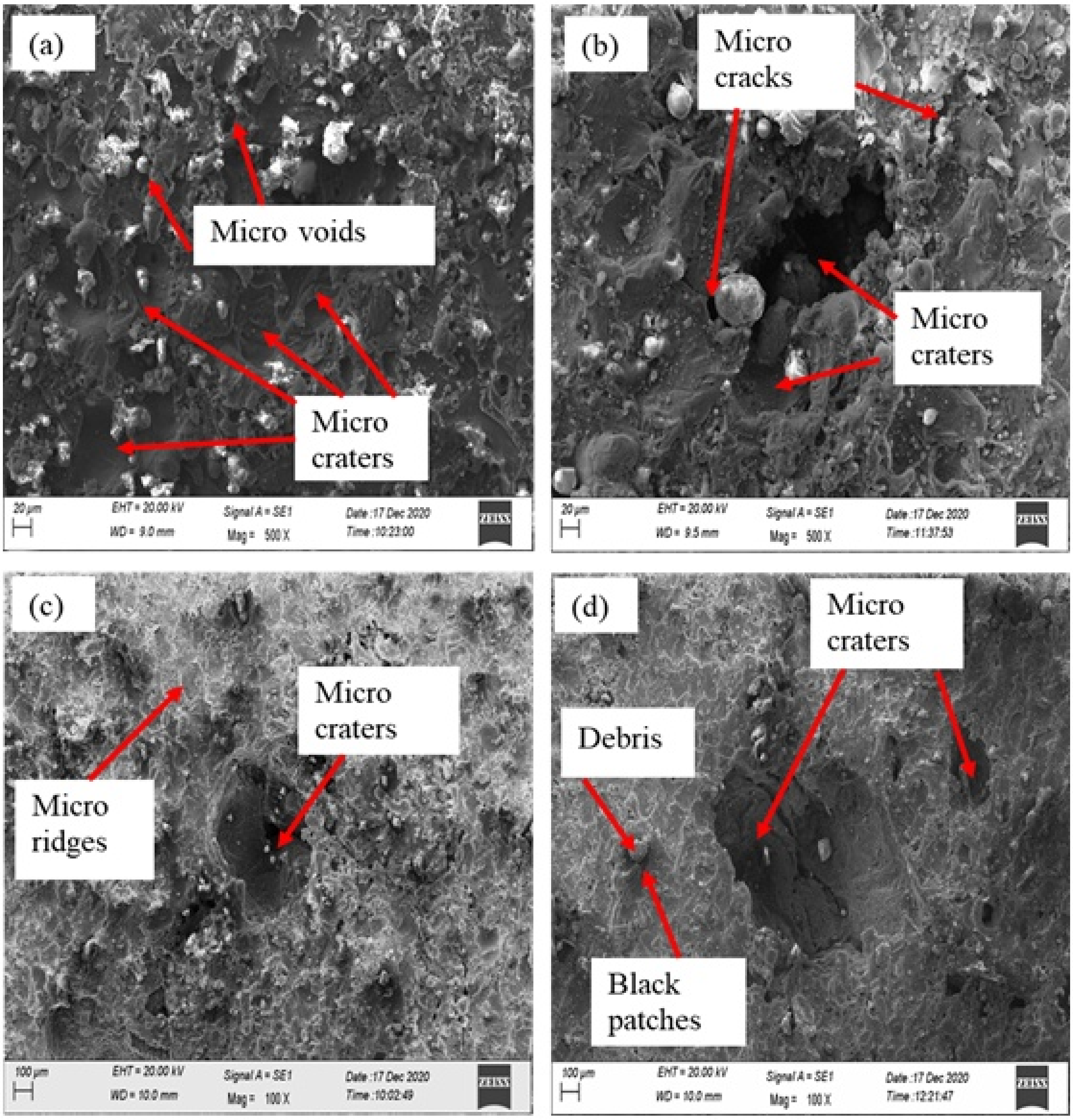

Fig. 5. Micrographs of machined surface for hybrid metal matrix composites: (a) B0A0, (b) B100A0, (C) B0A100, and (d) B75A25

Figure 5(c) shows the generation of micro ridges and micro craters. The pattern of micro ridges was uniform in one direction due to the generation of sparks in a particular direction. Plasma pressure is also responsible for creating a specified flow pattern of molten metal [7,8,28]. The micro craters were also observed indicating the removal of reinforcement at that place due to loosened bonding between the reinforcement and matrix by heating. In Figure 5(d) there were black patches, debris, and tiny and shallow micro craters on the machined surface. The black patches were cast due to the arcing that occurred during the machining of the composites B75A25. Soni et al. [13] found that the formation of surface defects such as micro cracks and microvoids occurred at a higher pulse on time in their investigation.

4 Conclusions

The machining of the prepared hybrid MMCs was carried out using wire electrical discharge machining (WEDM). The process parameters such as pulse current, pulse on time, gap voltage, and sample compositions that influence the output responses including material removal rate (MRR) and surface roughness (SR) were optimized through Taguchi and Gray relational analysis (GRA). The following conclusions may be drawn:

- The average values of MRR and SR for hybrid Al-Al_2O_3/B_4C composites were found to be decreased with the decrease in pulse on time and gap voltage. Also, it was found that the MRR and SR were increased with an increase up to a certain value of pulse current, and beyond that decreased.
- The optimum machining conditions were obtained through an integrated GRA-Taguchi analysis: sample composition of B_4C= 75 % and Al_2O_3 = 25 %, pulse on time of 32μs, pulse current of 2A, and gap voltage of 40 V.
- The results of ANOVA clearly showed the percentage contribution of sample composition of 3.08 %, pulse on time of 8.80 %, pulse current of 61.83%, and gap voltage of 13.65%.
- From SEM images, there was an occurrence of micro ridges, micro craters, micro-cracks, black patches, debris, and microvoids on the WEDMed surfaces.

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THE AUTHORS

Gupta M.K.
e-mail: mnnit.manoj@gmail.com
ORCID: 0000-0001-6174-364X

Gupta P.K.
e-mail: guptammmecpankaj@gmail.com
ORCID: -