EDM machining characteristics of bamboo leaf ash and alumina reinforced aluminum hybrid metal matrix composite using Multi-response optimization by grey relational analysis

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Abstract
In this research work, aluminum hybrid composites using bamboo leaf ash (BLA) and alumina have been fabricated via stir casting. Three hybrid composites viz: A713 + 2%BLA + 2%Al2O3, A713 + 2%BLA + 4%Al2O3, A713 + 4%BLA + 2%Al2O3 are fabricated successfully and EDM machining of these three composites is performed. The EDM machining experiments of the three hybrid composites, have been designed using Taguchi L27 orthogonal array design of experiments (DOE) considering current (A), duty cycle (%), gap voltage (V) and different percentage composition of the reinforcements. The effect of the EDM machining process parameters on the output responses such as surface roughness (Ra) and material removal rate (MRR) are evaluated using grey relational analysis.

1. Introduction

With the advancement in the technologies, the development of advanced materials like composites and hybrid composites becomes an integral part of the industries. Also, developing advanced materials which is economically viable is correspondingly an important aspect for the advanced materials. Therefore, in this research work, agro-based bamboo leaf ash (BLA) particles and alumina are used as reinforcements for fabricating aluminum alloy matrix composite.

Metal matrix composites are fabricated using a soft metal such as matrix and one or more particulates having high strength and hardness as reinforcing material [1]. The metal matrix composites (MMCs) find potential applications in automotive and aerospace industries where high strength to weight ratio is crucial. One of the preferred MMCs are aluminum-based metal matrix composites (AMMCs) for its attractive properties such as low density, high corrosion resistance, high strength and toughness [2]. Another feature of AMMCs is that agglomeration of ceramic reinforcement particle can be easily handled. When more than one reinforcement is incorporated into the aluminum alloy matrix, then it is called as aluminum hybrid metal matrix composites (AHMMCs). There are different methods for producing AHMMCs among which stir casting route is the most commonly used technique to fabricate AHMMCs as the stirring action enables uniform distribution of the reinforcing particles. Moreover, stirring force aids the wetting of the reinforcing particles to the matrix alloy. To increase wettability of the reinforcing particles to an acceptable amount of wettability, different techniques such as coating the reinforcing particles or preheating the ceramic particles are employed [3].

The machining of AMMCs is a major concern due to abrasive nature of the reinforcing particles via conventional techniques. The difficulties that encounter during the conventional machining methods are high tool wear rate and degradation of workpiece surface. Hence, unconventional machining methods are considered for machining of AHMMCs. Among the unconventional machining processes electric discharge machining (EDM) process is more feasible for machining AHMMCs.
EDM works on the thermo electrical process where material removal process takes place due to repeated series of electric sparks occurring between the electrodes of tool and anodic workpiece material. Irrespective of the hardness of the workpiece, material removal process takes place as long as the work piece material is electrically conductive in the EDM process. The basic principle involved is the tool connected to the negative side of the power supply and workpiece is connected to the positive side with a spark gap between them to form a shockwave. Both the tool and workpiece is immersed in the dielectric fluid which carries away the debris of machined part from the workpiece by continuous flow of dielectric fluid. The commonly used dielectric fluids are hydrocarbons such as kerosene, transformer oil, deionized water or silicon-based oil. The dielectric fluids have desired properties of high flash point, high oxidation stability and high dielectric strength which cause direct current (DC) arcing. The schematic diagram of the EDM process is illustrated in figure 1.

In EDM, the process parameters such as current, duty factor, and gap voltage and pulse duration play an important role on material removal rate (MRR) and surface finish [5]. These multiple performance measures depend on the EDM process parameters. Hence multi-objective optimization tools are essential for selecting best possible process parameters for more than one objective function known as multi-criteria optimization. Researchers have used several optimization tools and input parameters in electric discharge machining of different composites materials. Kumar et al [5] studied optimisation of EDM process parameters using ARAS, GRA and taguchi methods for machining aluminium alloy composite reinforced with B4C. Masum et al [6] employed GRA for machining nano-composite material made of CNT-carbon fiber. They have used different parameters such as peak current, pulse-on time, duty factor, and gap voltage to measure MRR and TWR. They concluded that the application of GRA technique has significantly improved MRR and TWR. Nadda et al [7] studied hybrid approach of AHP and TOPSIS for optimizing process parameters while EDM machining Co-WC composite. They reported the performance measures of MRR, TWR and Sr. The electrode tools employed were graphite and copper. Dey et al [8] performed electrical discharge machining on Aluminium alloy 6061 matrix with cenosphere fly ash by employing grey-based response surface methodology. They have found that lower values of pulse on time could increase electrode wear rate and higher material removal rate. Talla et al [9] conducted EDM experiments on aluminium and alumina power reinforced MMC using grey based principal component analysis. They have reported that along with machining parameters other factors such as thermal conductivity, coefficient of thermal expansion and density of the material majorly affects not only material removal rate but also surface roughness.

Multiple response optimisation technique such as grey relational analysis was used to select the best parameters combination to achieve highest metal removal rate and lowest surface roughness. In the present work Aluminium A713 is used as the matrix material and the reinforcements such as bamboo leaf ash (BLA) and alumina (Al$_2$O$_3$) with varying percentages were used for fabrication of hybrid metal matrix composites. The Experiments have been designed using Taguchi L27 orthogonal array design of experiments (DOE) considering current (A), duty cycle (%) and gap voltage (V) and different percentage of reinforcement compositions.

From the literature, it is found that there is no significant amount of work was carried out for machining AHMMC materials on EDM by varying different process parameters [10 – 13]. However there is no work reported to the machining of A713-Al$_2$O$_3$– BLA aluminium hybrid metal matrix composites. Furthermore, it was also found that the most of the process parameters used were pulse-on time, pulse-off time and current but in current research the authors have chosen peak current (A), duty cycle (%) and gap voltage (V) and different percentage compositions of reinforcements. Therefore, in the present work, an attempt has been made to investigate optimal process parameters for enhanced output parameters using orthogonal array of L27 experiments and develop a grey relational model.
2. Experimental details

2.1. Fabrication of the Aluminum hybrid composites

Aluminium base hybrid metal matrix composites are prepared by stir casting process. The ingots of A713 alloy was used as the matrix material, its chemical composition is given in wt% as Zinc (Zn): 8.0; copper (Cu): 0.5; Magnesium (Mg): 0.4; others: less than 0.5 and aluminium: balance. The reinforcing particles such as bamboo leaf ash (BLA) are prepared as ash particles with average size as 50 μm and alumina (Al₂O₃) particle with average grain size of 70 μm size are used for fabrication of AHMMCs.

A713 alloy sectioned ingots are fed to the stir casting equipment. These pieces are melted at the temperature of 750 °C and cooled to 650 °C temperature. To address the wettability issue of the reinforcing ceramic particles which are major setback in stir casting is preheated to 450 °C prior to mix to release all the moisture and trapped air between the particles to improve the wettability. Alaneme and Adewuyi [14] have pre-heated the BLA particles at 250 °C and Anil Kumar Birru [15] also pre-heated reinforcement particles at about 350°C to promote wettability.

These preheated particles are added to the melt at 650 °C and kept it for about 15 min. It is followed by stirring for 10 min with 600 rpm and held it for an hour at 650 °C followed by stirring for 10 min with 600 rpm and held it for an hour at 650 °C followed by stirring again for 5 min. After the second stirring, further the temperature is raised to 750 °C. At 750 °C the stirring is again continued with 600 rpm speed for 5 min and Al₂O₃ particles which are also preheated at the same temperature as BLA, are added while stirring and holding the mixture at this temperature of 750 °C for some more time of about 15 min. The molten material is then poured into the dies while pouring stirring is maintained. The same procedure is used for fabricating three different compositions of composites which are used as one of the parameters for machining. Another aspect of wettability is bamboo leaf ash particles float on the aluminium alloy liquid melt. This is may be due to the surface tension of the liquid melt and the lesser density of the bamboo leaf ash particles which leads to wettability issue of the ash particles. The particles reinforced composites developed with manual stirring may not overcome the poor wetting. It is noticed that particles tend to return to the surface when stirring is stopped as mentioned above, semi solid-state mixing at lower temperature of 650 °C is performed along i.e. bamboo leaf ash was add to the melt and stirring was carried out. It is also reported that that ceramic particles surface are generally enclosed in gas layer [16].

2.2. Machining process

The CNC EDM machine of Electronica machine tools India Ltd make was used for machining AHMMMC. The electrode of copper with dimensions 50 mm length and 12 mm diameter was used as the electrode. The EDM equipment used for the machining is shown in figure 2 and its specifications are given in table 1. The AHMMCs fabricated with different compositions were used as the workpiece were kept on the machine bed with a straight polarity.
The dielectric fluid used for flushing was commercially available EDM 30 oil. The dielectric pressure of $1.0 \text{ kgf cm}^{-2}$ was used to flush debris from the spark gap. The orthogonal array of experiments i.e. L$2^7$ procedure was applied for different input parameters such as peak current ($A$), Duty cycle ($\%$), gap voltage ($V$) and composition. The process parameters for machining the work piece material are given in Table 2. Each 27 experiments use separate copper tool each, which is as shown in figure 3(a) and machined components are shown in figure 3(b). The copper tool used is shown in figure 4.

The material removal rate and surface roughness were measured as the output responses. To measure the material removal rate (MRR) a digital mass balance was used. Taylor Hobson’s surtronic S128 equipment was used to measuring the surface roughness ($R_a$) is shown in figure 5. The sample composite material before and after machining is shown in figure 6.

3. Results and discussions

3.1. Grey relational analysis

Grey system theory was initiated by Dr Deng in the year 1982 [19]. Grey system is defined in terms of colours, if the information is completely known then it is represented as white system and if the information of the system is unknown then it is called as black system. If the system is partially complete or incomplete i.e. in between it is represented by grey colour. Therefore, the multiple output responses which can be nominal, higher and lower

![Figure 3. (a) Copper tools used and (b) EDM machined HMMCs.](image-url)
creates an uncertainty. Hence grey relational analysis is a simple statistical tool that converts multiple objective functions into single grey relational grade to avoid such uncertainty and vagueness [20]. The calculated experimental output responses such as MRR (g/min) and Ra (μm) are given in table 3.

In order to find the optimal process parameters combination multi criteria decision making technique such as Grey relational analysis (GRA) was employed. Therefore, the following steps are ensued for obtaining optimal process parameters combinations.

In this step the calculated experimental values are normalized to bring them between the range of 0 and 1.

In the current work, the machining characteristics such as MRR is desired higher whereas Ra is desired lower. Therefore, bigger the better response i.e. Equation (1) was considered for MRR and smaller the better i.e. Equation (2) for Ra was considered.
Where \( i = 1, \ldots, n \), \( m \) is the number of experiments and \( n \) is the number of response. \( y_{ki} \) is the original sequence of the present data. Grey relational coefficient (GRC) and grey relational grade (GRG) is calculated in this step. To analyse the relation between two systems the grey relational grade is obtained. GRC can be obtained by equation (3)

\[
\xi_i(k) = \frac{\Delta_{0i} + \zeta \Delta_{max}}{\Delta_{0i}(k) + \zeta \Delta_{max}}
\]

Where \( \Delta_{0i} \) is the deviation sequence of the given reference sequence and comparable sequence. \( \zeta \) = distinguishing coefficient \((0 \sim 1)\) in the present research \( \zeta = 0.5 \) is selected. 

\( \Delta_{min} \) = smallest value of \( \Delta_{0i} \) and \( \Delta_{max} \) = largest value of \( \Delta_{0i} \).

After calculating GRC values GRG values are obtained using the equation (4). The GRG now represents the single representative value of multi-responses.

\[
\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k)
\]

The normalization of the responses has been attempted and deviation sequence and GRG is identified in tables 4 and 5 respectively.

It is necessary to find effect of each process parameter at different levels on GRG. The obtained response values are given in table 6.

Table 6 represents mean of GRG and its significance levels of input parameters for machining. Significant can be known by the greater difference between the highest and lowest mean value of GRG. Therefore, from
Table 4. Normalized data and corresponding deviation sequence.

| S.NO | Normalization | Deviation Sequence |
|------|---------------|--------------------|
|      | MRR (gm/min)  | Rₐ (μm)           | MRR (gm/min) | Rₐ (μm) |
| 1    | 0.0000        | 1.0000             | 1.0000       | 0.0000  |
| 2    | 0.0909        | 0.9714             | 0.9091       | 0.0286  |
| 3    | 0.0909        | 0.9714             | 0.9091       | 0.0286  |
| 4    | 0.0909        | 0.9571             | 0.9091       | 0.0429  |
| 5    | 0.4545        | 0.9571             | 0.5455       | 0.0429  |
| 6    | 0.4545        | 0.9429             | 0.5455       | 0.0571  |
| 7    | 0.7273        | 0.9429             | 0.2727       | 0.0571  |
| 8    | 0.5455        | 0.9429             | 0.4545       | 0.0571  |
| 9    | 0.6364        | 0.9000             | 0.3636       | 0.1000  |
| 10   | 0.4545        | 0.8143             | 0.5455       | 0.1857  |
| 11   | 0.5455        | 0.8714             | 0.4545       | 0.1286  |
| 12   | 0.4545        | 0.8714             | 0.5455       | 0.1286  |
| 13   | 0.4545        | 0.8857             | 0.5455       | 0.1143  |
| 14   | 0.6364        | 0.8429             | 0.3636       | 0.1571  |
| 15   | 0.5455        | 0.7000             | 0.4545       | 0.3000  |
| 16   | 0.5455        | 0.8143             | 0.4545       | 0.1857  |
| 17   | 0.5455        | 0.7143             | 0.5455       | 0.2857  |
| 18   | 0.6364        | 0.7286             | 0.3636       | 0.2714  |
| 19   | 0.5455        | 0.6714             | 0.5455       | 0.3286  |
| 20   | 0.5455        | 0.4429             | 0.4545       | 0.5371  |
| 21   | 0.6364        | 0.4429             | 0.3636       | 0.5371  |
| 22   | 0.6364        | 0.4571             | 0.2727       | 0.5429  |
| 23   | 0.2723        | 0.2143             | 0.2727       | 0.7857  |
| 24   | 0.1812        | 0.1286             | 0.1818       | 0.8714  |
| 25   | 0.2723        | 0.1000             | 0.2727       | 0.9000  |
| 26   | 1.0000        | 0.0000             | 0.0000       | 1.0000  |
| 27   | 1.0000        | 0.0143             | 0.0000       | 0.9857  |

Table 5. Obtained GRC and GRG values for all the experiments.

| S.NO | GRC values | GRG | Order |
|------|------------|-----|-------|
|      | MRR (gm/min) | Rₐ (μm) |       |
| 1    | 0.3333      | 1.0000  | 0.6667 | 8     |
| 2    | 0.3548      | 0.9459  | 0.6504 | 11    |
| 3    | 0.3548      | 0.9459  | 0.6504 | 11    |
| 4    | 0.3548      | 0.9211  | 0.6379 | 14    |
| 5    | 0.4783      | 0.9211  | 0.6997 | 4     |
| 6    | 0.4783      | 0.8974  | 0.6878 | 5     |
| 7    | 0.6471      | 0.8974  | 0.7222 | 1     |
| 8    | 0.5238      | 0.8974  | 0.7106 | 2     |
| 9    | 0.5789      | 0.8333  | 0.7061 | 3     |
| 10   | 0.4783      | 0.7292  | 0.6037 | 18    |
| 11   | 0.5238      | 0.7955  | 0.6596 | 10    |
| 12   | 0.4783      | 0.7955  | 0.6369 | 15    |
| 13   | 0.4783      | 0.8140  | 0.6461 | 13    |
| 14   | 0.5789      | 0.7609  | 0.6699 | 6     |
| 15   | 0.5238      | 0.6250  | 0.5744 | 20    |
| 16   | 0.5238      | 0.7292  | 0.6265 | 16    |
| 17   | 0.5238      | 0.6364  | 0.5801 | 19    |
| 18   | 0.5789      | 0.6481  | 0.6135 | 17    |
| 19   | 0.5238      | 0.6034  | 0.5463 | 21    |
| 20   | 0.5238      | 0.6304  | 0.4984 | 27    |
| 21   | 0.5238      | 0.4730  | 0.5260 | 24    |
| 22   | 0.6471      | 0.4795  | 0.5633 | 22    |
| 23   | 0.6471      | 0.3889  | 0.5180 | 25    |
| 24   | 0.7333      | 0.3646  | 0.5490 | 23    |
| 25   | 0.6471      | 0.3571  | 0.5021 | 26    |
| 26   | 1.0000      | 0.3333  | 0.6667 | 8     |
| 27   | 1.0000      | 0.3365  | 0.6683 | 7     |
Table 6. Response table of GRG.

| Parameter          | Level 1 | Level 2 | Level 3 | Optimum level | Main effect (Max-min) | Rank |
|--------------------|---------|---------|---------|---------------|-----------------------|------|
| A: Peak Current (A)| 0.6869  | 0.6234  | 0.5617  | 1             | 0.1252                | 1    |
| B: Duty cycle (%)  | 0.6062  | 0.6162  | 0.6496  | 3             | 0.0434                | 2    |
| C: Gap Voltage (V) | 0.602   | 0.6403  | 0.6297  | 2             | 0.0383                | 3    |
| D: Composition     | 0.6328  | 0.6037  | 0.6355  | 3             | 0.0318                | 4    |
| Total mean value of GRG |         |         |         |               | 0.624                 |      |

Table 7. ANOVA of GRG.

| Source                | DF | Seq SS   | Adj SS   | Adj MS   | F       | P       |
|-----------------------|----|----------|----------|----------|---------|---------|
| Peak Current (A)       | 2  | 0.070531 | 0.070531 | 0.035265 | 18.58   | 0       |
| Duty Cycle (%)         | 2  | 0.009287 | 0.009287 | 0.004644 | 2.45    | 0.115   |
| Gap Voltage (V)        | 2  | 0.007051 | 0.007051 | 0.003526 | 1.86    | 0.185   |
| Composition            | 2  | 0.005578 | 0.005578 | 0.002789 | 1.47    | 0.256   |
| Error                 | 18 | 0.034172 | 0.034172 | 0.001898 |         |         |
| Total                 | 26 | 0.126619 |          |          |         |         |

Table 6 it can be observed that peak current is the most significant factor affecting the GRG followed by duty factor gap voltage and composition. Among all the process parameters, peak current plays an important role for enhancing material removal rate and decreasing the surface roughness.

The main effect plots of GRG for significance level of process parameters is shown in figure 7. From figure 7, it can be concluded that as the peak current is increasing from 7 A to 9 A there is a decrement in the GRG value. With an increase in Duty factor GRG value is also increasing. As the Gap voltage is increased from level 1 to level 2 i.e. from 45 V to 55 V GRG increased and upon further increment of gap voltage to 65 V GRG value decreased. Furthermore, it is observed that GRG value is decreased when composition has changed from 1 to 2 and GRG increased even more with change of composition from 2 to 3. Hence from the main effect plots of the process parameters the best suitable process parameters to have enhanced machining characteristics are found to be 7 A, 90%, 55 V and composition 3.

3.2. ANOVA

Analysis of variance (ANOVA) is performed with calculated GRG values. ANOVA gives contribution of each independent input process parameters which affects the performance of the output responses. Table 7 gives the ANOVA result of GRG. From the ANOVA table it is found that peak current is the most significant process
is the mean GRG, parameter which affects the machining as the p-value is less than 0.05 at 95% confidence level [21]. The other process parameters such as duty cycle, gap voltage and composition are less significant.

### 3.3. Confirmation test

Finally, a confirmation experiment is done to authenticate the optimal parameter setting. In this step an improvement in the Grey relational grade from the initial experiment to the optimum parameter combination experiment is obtained. The predicted GRG can be obtained from the equation (5).

\[
\bar{\gamma} = \gamma_m + \sum_{i=1}^{a} (\bar{\gamma} + \gamma_m)
\]

Where \(\gamma_m\) is the mean GRG, \(\bar{\gamma}\) is the GRG at optimum process parameter combination. Optimum process parameter combination is selected from the response table having highest GRG value. Thus the optimal setting parameter combination is from table 6 is A1B3C2D3.

From table 8, MRR is increased from 0.04 gm min\(^{-1}\) to 0.13 gm min\(^{-1}\) and \(R_s\) has increased from 0.5 \(\mu m\) to 0.8 \(\mu m\). It can be observed that predicted GRG has enhanced from 0.6667 to 0.7403 with an improvement of 0.0736. Finally upon conduction of the experiment it is observed that GRG has considerably increased to 0.8271 with an improvement of 0.1604. Hence it can be concluded that Grey relational analysis significantly improves the multiple performance characteristics in electric discharge machining.

### 3.4. Analysis of surface morphologies

SEM images of different experimental conditions (1, 13 and optimal condition) are shown in figure 8. The images show the presence of redeposited molten material, craters and micro and macro pores and cracks. For experimental condition 1 i.e. peak current 7 A, duty cycle 60%, gap voltage 45 V and composition 1; redeposited molten material, discharge crater and small surface cracks can be observed in figure 8(a). As peak current, duty cycle, gap voltage has increased in experiment 13 for the same composition; redeposited molten material ridges have been increased significantly. Another noteworthy point to mention is that surface crack density which was small in experiment was considerably increased as input parameters have been increased to 8 A, 75% and 65 V respectively. The EDM micrograph figure 8(b) has exhibited high surface roughness when compared to other machined surfaces. Furthermore, upon increase of peak current to 8 A, duty cycle 75% and voltage gap 65 V larger and deeper discharge craters are observed which is attributed to increased discharge energy. Prakash et al [22] reported similar findings that the generated discharge energy proliferates and penetrates deeper into the machined surfaced. They also reported that increased current generates more discharge energy which melts the excess material from the surface of the machined part in form of debris. Theses formed debris cannot be flushed easily and sticks to the periphery of craters results in formations of oxides and carbides. Hence the surface quality is deteriorated with the increase of high ridges of redeposited molten material. In the current research work, prevention of large and wider craters, ridges of redeposited molten material and surface crack density and pores are addressed by optimizing the process parameters. The reduced surface roughness and discharge crater is shown in figure 8(c). At optimal process parameters combination i.e. 7 A, 90%, 55 V and composition 3 the generated thermal energy is optimum which removes the material in form of small debris and flushes away easily reducing the formation of rough surface and improves the material removal rate.

### 3.5. Influence of EDM input parameters on material removal rate and surface roughness

To find the effect of individual process parameters on the material removal rate and surface roughness has been shown by different mean effect plots in figure 9 and 10 respectively. From figure 9 it is clear that as peak current is increased from 7 A to 9 A the material removal rate increases. This can be attributed to more spark energy generated within the inter-electrode gap (IEG) which leads to an increase in temperature as a result more material melts and subsequently, increases MRR [23]. Some of the studies further reported that as the peak

| Table 8. Confirmation result. | Initial Experiment | Prediction | Experiment |
|-----------------------------|-------------------|-----------|------------|
| Level | A1B1C1D1 | A1B3C2D3 | A1B3C2D3 |
| MRR (gm/min) | 0.04 | — | 0.13 |
| \(R_s\) (\(\mu m\)) | 0.5 | — | 0.8 |
| GRG | 0.6667 | 0.7403 | 0.8271 |
| Improvement | — | 0.0736 | 0.1604 |
current increases discharge energy channel diameter also increases. This increases crater diameter and depth as a result MRR increases [24]. The obtained results are in agreement with equation (6) which gives the total energy of a single pulse EDM.

\[
W = \int_0^{t_n} u(t) i(t) dt \ldots \ldots
\]  

(6)

Where \(u(t)\) is the processing voltage between electrode tool and workpiece material, \(i(t)\) is the working current, \(t_k\) is the pulse duration (the EDM spark maintain time). Hence, it is obvious that the larger peak current will
produce large EDM spark energy (W). Therefore, large EDM spark energy (W) in turn produces higher MRR [25]. On the other hand, it is observed in Fig. 10 that surface quality gets deteriorates as the peak current increases from 7 A to 9 A. This is due to the increase in quantity of the material removal rate. The higher MRR results in large and deep craters when discharge energy is raised. In a study conducted by Kumar et al [4] concluded that surface characteristics of the composites are affected by peak current. This is attributed to the enhanced bombarding forces between the electrode and material. In figure 9 it can be observed that as the duty cycle increases from 60% to 90%, the material removal rate is also enhanced. The duty cycle is given in terms of the percentage value of the ratio of the pulse duration to the total time of the cycle as calculated in equation (7).

\[
\text{Duty Cycle (\%)} = \frac{\text{Pulse duration}}{\text{total cycle time}} \times 100 \ldots (7)
\]

From equation (7) it can be observed that the small duty cycle indicates high pulse off time which results in low melting and vaporization of the workpiece material and subsequently lowers the material removal rate [26]. A similar trend is noticed for the surface roughness at lower duty cycle. The surface roughness is low at lower duty cycle and as the duty cycle increases the surface roughness also increases as shown in figure 9. From the mean effect plots for MRR with respect to gap voltage as shown in figure 9, it can be inferred that initially, as gap voltage increases from 45 V to 55 V MRR increases but when gap voltage was further increased to 65 V MRR decreases. The decrease in the MRR may be attributed to higher gap voltage which increases time for bridging the discharge with ions and electrons as a result the material removal rate slows down [27]. The other reasons contributing to lower MRR when gap voltage is high are less energy density, energy loss, and lower IEG values [28]. However, the surface roughness decreases when gap voltage increases. Higher gap voltage has an inverse relationship with surface roughness due to gap resistance. This hinders the passage of discharge from an electrode to workpiece material [29]. To further assess the effect of composition on the machining characteristics it can be observed that at composition 3 both MRR and Ra increases. Initially, when the composition is changed from 1 to 2 the MRR has decreased this is due to an increase in the wt% of hard ceramic Al₂O₃ particles to 4% when BLA is kept constant with 2%. In level 3, the composition 2 is changed to composition 3 where the wt% of hard ceramic Al₂O₃ particles has been reduced to 2% wt by increasing wt% of BLA from 2% to 4%. The increase in the MRR can be attributed to the porosity of the produce hybrid metal matrix. Birru et al [15] reported that when BLA wt% was increased the density was decreased and porosity was increased. Therefore, enhanced MRR was observed in the in present study when composition is at level 3.

4. Conclusions

Aluminium alloy A713 reinforced with Al203 and BLA was successfully fabricated by stir casting route and material was machined effectively by EDM approach by varying different input process parameters which affects the performance characteristics. Grey relational analysis statistical approach was employed to find the optimal process parameter combination for enhanced output responses and following conclusions were drawn:
1. The best suitable input process parameters alike peak current 7 A, duty cycle 90%, gap voltage 55 V and composition 3 (A713 + 2%A2O3 + 4% BLA) were obtained by GRA for attaining improved MRR and decreased Ra.

2. The response table (peak current 7 A, duty cycle 90%, gap voltage 55 V and composition 3) is out of L27.

3. The confirmation test exhibits an improvement in GRG value of the predicted and experimental condition by 0.0736 and 0.1604 from the initial experimental condition.

4. From the ANOVA table peak current is the most significant factor affecting the output responses.

5. Surface morphologies were evaluated by SEM, the optical condition experiment has significantly reduced the surface roughness by decreasing the width and depth of discharge crater.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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