

Parameter optimization for wire-cut electrical discharge machining of stir cast AA6063 alloy/SiC (black and green) using Taguchi method with grey relational analysis

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The present investigation aimed to determine the optimal parameters for wire-cut electrical discharge machining (WEDM) for stir cast aluminum alloy AA6063 at 850°C reinforced with 10 wt.% green SiC (SiC_g) and black SiC (SiC_b) particles. The WEDM machining parameters, such as pulse on time (T_{ON}), wire feed (WF) rate, and flushing pressure (FP) of the resultant stir cast AA6063/SiC_b and AA6063/SiC_g composites, were optimized using the Taguchi method with L9 orthogonal array to estimate the responses, such as surface roughness and metal removal rate. Further, through grey relational analysis, the finest parameters for WEDM of AA6063/SiC_b and AA6063/SiC_g composites were evaluated as $T_{ON} = 50 \mu s$, WF rate = 18 m/min, and FP = 3 MPa. With the optimum parameters obtained, conformational experiments were conducted, and the scanning electron microscopic images were recorded, along with the energy-dispersive X-ray (EDX) spectroscopic data of the worn surfaces and debris. From the EDX mapping images of the machined surface, it was evident that AA6063/SiC_b displays a more polished surface than AA6063/SiC_g. However, for applications requiring a high metal removal rate, AA6063/SiC_g displays better results than AA6063/SiC_b.

Keywords: AA6063, silicon carbide, wire-cut electrical discharge machining, stir cast, Taguchi method, grey relational analysis

1. Introduction

Composite is a term used when two or more unlike materials are mixed or combined, with the subsequent product having much better properties than each of the precursor materials [1]. One such kind of composite is the metal matrix composite (MMC), in which the metal constitutes the matrix and required reinforcements are added to the matrix to enhance the essential properties of the composite [2]. Because of the enhanced properties of MMCs compared with their pristine form, they have a wide range of applications in varied industries, such as marine vessels [3], structural engineering [4], manufacturing of engineering goods [5], machining industries [6], automobiles [7], aerospace [8], etc. From this, it is

clear that MMCs are widely useful in applications wherein sturdy mechanical properties constitute the major requirement. With the drastic advancement in the industrial sector, there are numerous reports emphasizing the enhancement of the mechanical behavior of metals, especially aluminum (Al) and its alloys. Al and its alloys are known for their low-density nature, but they have high strength comparable to that of steel [9]. Besides, Al has natural corrosion resistance behavior, whereby the Al₂O₃ film formed over the surface acts as a good passivation layer, preventing further corrosion [10]. Recently, due to the advancements in industrial technology and its subsequent applications, there is a requirement to improve the mechanical properties of Al, which can be made possible using MMCs. Therefore, researchers and scientists have been trying to reinforce the Al matrix

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with suitable materials without deteriorating the former's inherent properties. One such reinforcement is the silicon carbide (SiC) particle. SiC particle is most widely reported due to its low cost and wide availability and because it imparts high strength to the matrix owing to its high Young's modulus [11]. Further, SiC particles are known for their lightweight property [12], and therefore, when reinforced in aluminum alloys, they can effectively improve the Young's modulus without deteriorating the lightweight applications. Hu et al. [13] fabricated Al-based MMCs by using SiC particles to reinforce A356 and 6061 alloys, facilitated by vacuum-assisted high-pressure die casting. The tensile strength of A356 and 6061 alloys reinforced with SiC particles were found to be 286 MPa and 246 MPa. Likewise, Mousavian et al. [14] fabricated Al-SiC composite using the hot extrusion process. Other metallic constituents, such as copper, chromium, and titanium, were also supplemented separately along with the composite. In all the cases, the yield strength was higher than that of the A356 alloys, substantiating the fact that SiC improves the yield strength of the Al matrix. Similarly, Fenghong et al. [15] prepared Al6061 composites with the introduction of SiC and WC. The presence of reinforcing materials improved the hardness, tensile strength, and wear resistance of the hybrid composites. Even though many reports in the literature have dealt with the reinforcement of the Al matrix with SiC, while fabricating the Al-SiC composite through the stir casting technique, the Al_4C_3 phase is formed, which deteriorates the performance of the composite by converting it to $\text{Al}(\text{OH})_3$ in the presence of atmospheric moisture [16]. In the commercial market, SiC is available in green (SiC_g) and black (SiC_b) grades, which depend upon the preparation technique. SiC_g and SiC_b have different mechanical properties as the percentage of SiC in each material is different; SiC_g has a higher percentage of SiC than SiC_b . Therefore, it is clear that SiC_b has more SiO_2 in its composition. Moreover, it has been reported that the presence of SiO_2 can considerably reduce the formation of the Al_4C_3 phase, resulting in a better microstructure and impact strength of the Al-SiC composite [16].

Even though SiC_b is reported to be the apt reinforcement material for Al and its alloys, reports dealing with a comparative study of the machining property of SiC_g - and SiC_b -reinforced Al matrixes are very limited. Further, it has been reported that if the reinforcement is harder than the matrix material, then the reinforcement induces the precipitation hardening of the metal matrix [17]. Precipitation hardening is nothing but the obstruction of the dislocation movement of the metal matrix by the impurity phase, resulting in the reduction of plastic deformation. Upon improvement in the strength of the Al MMCs, it is difficult to process or machine the MMCs similar to that of the pristine Al. Therefore, the machining parameters have to be changed or optimized according to the reinforcement and matrix materials.

One of the industrially used machining processes is wire-cut electrical discharge machining (WEDM), wherein unwanted materials are removed by erosion triggered by spark discharges to obtain the desired shape [18]. WEDM is widely used for machining MMCs due to its efficient processing capabilities toward brittle and hard materials, providing control over complex shapes and designs [19, 20]. Owing to its ability to develop intricate structures that otherwise are not possible, it has applications in various industrial divisions. But the machining parameters have a substantial influence on the production rate and quality of the machined products. In this context, to carry out an efficient machining process, the processing parameters have to be optimized for each MMC because the reinforcement, when added to the metal matrix, enhances the mechanical behavior of the resultant MMC. The primary processing parameters of WEDM include applied voltage, flushing pressure (FP), pulse on and off time, wire feed (WF) rate, dielectric medium, etc. [21]. Manually, optimizing all the processing parameters requires a large number of experiments, which is a tedious and time-consuming process. Therefore, computational techniques are most widely preferred to optimize the process parameters since they require limited experiments, are time efficient, and are cost-effective. In this regard, many results for the optimization of WEDM parameters for the machining of Al and

other alloys have been reported. Nguyen et al. [22] utilized Taguchi-based grey relational analysis to optimize the machining process of high-chromium steel and elucidated the optimum parameters, such as peak current, gap voltage, pulse on time, and pulse off time, on responses such as material removal rate (MRR), surface roughness, microhardness, and average white layer thickness. Selvakumar et al. [23] optimized the WEDM parameters of machining 5083 Al alloy, such as pulse on time, pulse off time, peak current, and wire tension using Taguchi design (L9 orthogonal array) for responses such as maximum cutting speed and minimum surface roughness. Mandal et al. [24] utilized Taguchi grey relational analysis method to optimize the machining parameters of WEDM against Al 7075 alloy. The WEDM input parameters, such as pulse on and pulse off times, FP, and applied voltage were studied to analyze the responses, such as machining speed and corner inaccuracy. Through grey relational analysis, a set of parameters that show the highest ranking was elucidated. Further, the confirmational experimental results coincide with the values predicted from regression equations.

In this context, the present work focuses on the preparation of AA6063/SiC_g and AA6063/SiC_b composites through the stir casting process, and the influence of the components on the WEDM processing parameters is evaluated. The machining parameters such as pulse on time, WF rate, and FP are optimized for each SiC type through the Taguchi method with grey relational analysis, and the process outcomes are experimentally evaluated.

2. Material and methods

2.1. Materials required

The aluminum alloy AA6063 in rod form was obtained from Parshwamani Metals, Mumbai, Maharashtra, India. The material composition of AA6063 includes Al (≤ 97.5 wt.%), Si (0.20–0.60 wt.%), Mg (0.45–0.90 wt.%), Cu (≤ 0.10 wt.%), Mn (≤ 0.10 wt.%), Fe (≤ 0.35 wt.%), Ti (≤ 0.10 wt.%), Cr (≤ 0.10 wt.%), Zn (≤ 0.10 wt.%), and others (≤ 0.15 wt.%). SiC_g and SiC_b of size 100 μm , used as reinforcement, were obtained

from Parshwamani Metals. SiC_g has $>97\%$ SiC, whereas SiC_b has $>95\%$ SiC.

2.2. Fabrication of composites using stir casting technique

In the present work, 100- μm -sized SiC_b and SiC_g particles were added separately to the AA6063 aluminum alloy matrix as reinforcement through the stir casting technique. First, the AA6063 matrix is melted in a graphite crucible at 850°C. The melted AA6063 was stirred using a graphite stirrer for 45 min at 250 rpm. SiC_b and SiC_g were added separately to the melted AA6063. Before the addition, the SiC particles were preheated to 250°C to enable even mixing in the melted AA6063. The preheating process along with the stir casting process enabled good wetting and uniform distribution of the SiC particles in the molten AA6063. After a successful stir casting process, the molten composite was poured into a mold and cooled at room temperature; the blocks were removed and used for conducting experiments on WEDM.

2.3. WEDM process

The WEDM machining process was performed using the Agie Charmilles (Biel, Switzerland) WEDM machine. Even though many parameters affect the machining of a composite using WEDM, the present work emphasizes the parameters such as pulse on time (T_{ON}), WF rate, and FP, which are considered the input variables. T_{ON} is an important parameter since anodic dissolution happens during the T_{ON} stage and, therefore, material removal occurs at this stage. The WF rate also directly influences the material removal process, but it is affected by the parameter FP. When the WF rate is high, the material is eroded rapidly, which affects the surface finish, but with high FP, the eroded materials can be efficiently cleared from the machining surface, leading to a better surface finish. Therefore, WF rate and FP were included as the process parameters for the optimization process. Other important parameters are pulse off time (T_{OFF}), voltage, and current. Optimum T_{OFF} is required to remove all the dissolved products from

Table 1. Input machining parameters for both AA6063/SiC_g and AA6063/SiC_b composites and their levels

Factor	Symbol	Units	Level		
			Level 1	Level 2	Level 3
Pulse on time	T_{ON}	μs	50	75	100
Wire Feed	WF	m/min	6	12	18
Flushing Pressure	FP	MPa	1	2	3

the machining area with running water and this also restricts the increase in temperature of the workpiece. However, high T_{OFF} leads to an unnecessary increase in the machining time, and therefore, T_{OFF} was kept constant at 50 μs . Likewise, the voltage and the current were kept constant for the experimental studies as 60 V and 6 A, respectively. Table 1 displays the input parameters and their levels for designing an L9 orthogonal array for machining both AA6063/SiC_g and AA6063/SiC_b composites. The input parameters were set as per the preliminary experimental results, where higher values of T_{ON} and WF rate lead to a decline in the surface finish, while lower T_{ON} and WF rate result in negligible change. The lower and higher levels of FP were selected in such a way that beyond the set point, the change in results was insignificant. Using an orthogonal array, the experimental size can be considerably reduced.

Here, AA6063/SiC_g or AA6063/SiC_b of dimension 200 mm $\times$ 80 mm $\times$ 20 mm (length $\times$ breadth $\times$ height) was used as the workpiece, whereas brass wire with a diameter of 0.25 mm was used as the machining wire electrode. Deionized water was selected as the dielectric medium for all the experimental trials. The workpiece was fixed using a clamp to avoid any kind of disturbances during the WEDM process. Other machining parameters, such as the temperature of the dielectric medium and angle of machining, were kept constant at 27°C and 90°, respectively. The machining was performed along a 20-mm-diameter region for all the samples. During machining, the continuous flow of the dielectric medium was ensured. Through the Taguchi method, an L9 orthogonal array was constructed using three factors and three levels using Minitab statistical software (Table 2). As per the experimental design, WEDM processes were carried out for both AA6063/SiC_g

and AA6063/SiC_b. From each experimental analysis, the MRR and surface roughness (R_a) were calculated. The MRR of the machining process was evaluated through the following equation [25]:

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

where the initial and final weights of the samples are denoted as W_i and W_f , t represents the time, and ρ is the density of the material. The R_a values of the machined samples were evaluated using the surface roughness tester (SJ-410; Mitutoyo, Aurora, United States). Here, a 2- μm tip inclined at 60° was used to analyze the surface. The surface was scanned for 2 mm at a speed of 10 mm/min. Three measurements were carried out at random positions. The complete profile was then leveled using the least-squares method and filtered using the Gaussian profile filter setting the cutoff length as 0.8 mm. For better precision, each experiment was conducted thrice, and the average value is provided. In the machining process through WEDM, higher MRR and lower R_a constitute efficient performance of the process and, therefore, we selected the same for the grey relational analysis. Grey relational analysis was performed to construct a single response from the actual multiple responses. This technique enables easy grading of parameters according to the final single constructed response. To perform this task, at first, the responses were normalized, wherein the equation for lower-the-better strategy is expressed as follows [26],

$$X_i(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (2)$$

For larger-the-better strategy, the expression is as follows:

$$X_i(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (3)$$

Table 2. Experimental design for L9 orthogonal array and the experimental data

Sl. no.	T_{ON}	WF	FP	AA6063/SiC _b		AA6063/SiC _g	
				MRR-1 (mm ³ /min)	R_a -1 (μm)	MRR-2 (mm ³ /min)	R_a -2 (μm)
1	50	6	1	8.57	1.88	8.81	1.82
2	50	12	2	9.09	1.59	9.27	1.63
3	50	18	3	9.78	1.11	9.94	1.24
4	75	6	2	10.51	1.65	10.83	1.69
5	75	12	3	11.23	1.67	11.19	1.81
6	75	18	1	11.86	2.45	11.98	2.40
7	100	6	3	13.25	2.56	13.05	2.72
8	100	12	1	13.52	3.09	13.66	3.05
9	100	18	2	13.61	3.10	14.13	3.17

MRR-1 and R_a -1 = MRR and surface roughness of AA6063/SiC_b; MRR-2 and R_a -2 = MRR and surface roughness of AA6063/SiC_g.

All the experiments were conducted thrice, and the average values are provided.

FP, flushing pressure; MRR, material removal rate; T_{ON} , pulse on time; WF, wire feed.

where $X_i(k)$ is the normalized value, $\max x_i(k)$ and $\min x_i(k)$ are the maximum and minimum of the experimental values, $x_i(k)$ is the experimental value, and k is the position of the response. After obtaining the normalized value, the grey relational coefficient was evaluated through the following equation [26]:

$$\xi_i(k) = \frac{\Delta \min + \Psi \Delta \max}{\Delta 0_i(k) + \Psi \Delta \max} \quad (4)$$

where $\Delta 0_i(k) = \|x_i(k) - x_i(k)\|$, $\Delta \min$ and $\Delta \max$ are the minimum and maximum values of $\Delta 0_i$, and Ψ is the distinguishing coefficient whose value is taken as 0.5. The grey relational grade (GRG) was calculated using the following expression [26]:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \quad (5)$$

Here, n denotes the number of responses. From the GRG values, the highest values were chosen as the optimal parameters for better performance of the WEDM process.

2.4. Characterization techniques

The crystalline phases of SiC_b, SiC_g, and Al were evaluated through the X-ray diffraction (XRD) pattern recorded using an X-ray diffractometer (D8 Advance ECO XRD Systems; Bruker,

Massachusetts, United States of America). The morphologies of SiC_b and SiC_g were observed from the scanning electron microscopic (SEM) images (EVO 18, Carl Zeiss, Oberkochen, Germany). The elemental constitution over the machined surfaces of SiC_b- and SiC_g-reinforced AA6063 was examined through energy-dispersive X-ray spectroscopic (EDX) mapping analysis. Further, the elemental composition of the debris was also analyzed using EDX.

3. Results and discussion

The crystalline phases of SiC_b, SiC_g, and AA6063 were determined through XRD analysis and are shown in Figures 1A–1C. Figures 1A and 1B display the diffraction patterns of SiC_b and SiC_g, respectively, where the peaks matched well with the standard Joint Committee on Powder Diffraction Standards (JCPDS) no. 00-001-1118. Apart from the SiC peaks, the diffraction patterns display impurity phases attributed to the fact that the obtained SiC_b and SiC_g are not 100% pure. The impurities may have been introduced during the preparation stage. Further, another noteworthy feature is that the intensities of the impurity phases are lower in the case of SiC_g compared to the same for SiC_b, substantiating the fact that a higher percentage of SiC phase is present in SiC_g.

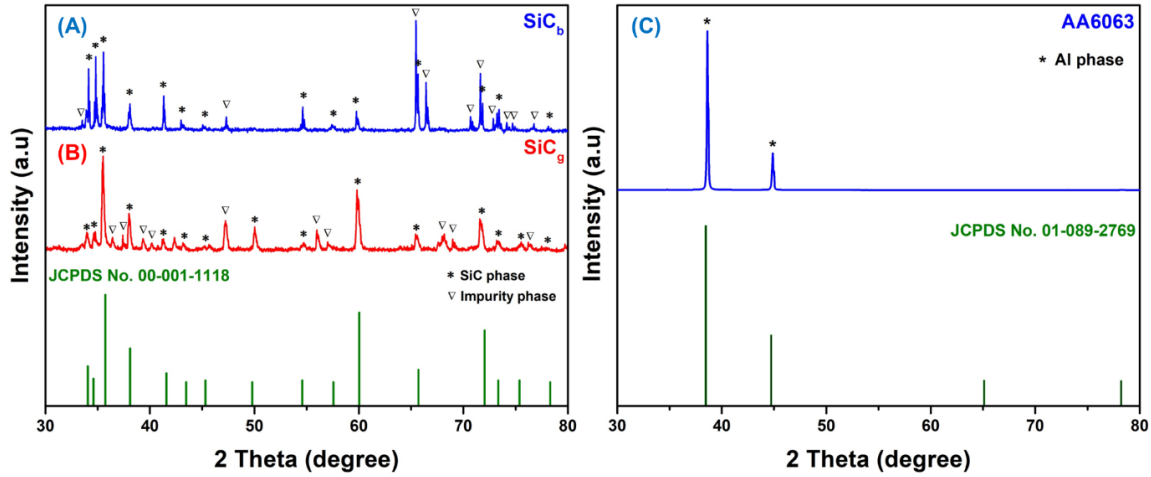


Fig. 1. XRD patterns of (A) SiC_b , (B) SiC_g , and (C) AA6063. XRD, X-ray diffraction

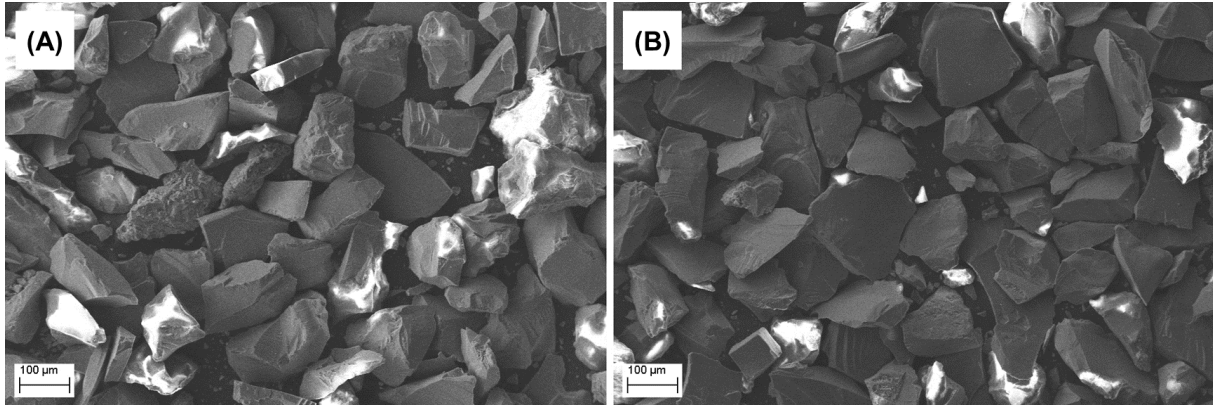


Fig. 2. SEM images of (A) SiC_b and (B) SiC_g . SEM, scanning electron microscopy

than in SiC_b . Figure 1C shows the XRD pattern of AA6063, wherein the diffraction peaks corresponding to Al are validated through JCPDS No. 01-089-2769 [27]. From the diffraction pattern, the crystal system of the Al phase is estimated as cubic, with a space group of Fm-3m. Even though alloying elements such as silicon, magnesium, etc. are present in AA6063, their presence is not seen in the diffraction pattern, which validates the completion of the alloying process.

The morphological properties of the purchased SiC_b and SiC_g were assessed from the SEM micrographs, which are provided in Figures 2A and 2B. From the images, it is clear that the SiC particles are in the size of $\sim 100 \mu\text{m}$, with irregularly shaped blocks. Further, SiC_g shows sharp edges compared

to SiC_b , suggesting the extra-brittle nature of SiC_g .

After the stir casting process, wherein SiC_b and SiC_g were added to AA6063 as reinforcements separately, they were subjected to the WEDM process. The WEDM process was carried out according to the constructed L9 orthogonal array, whereby the MRR and R_a of AA6063/ SiC_g and AA6063/ SiC_b were calculated, as summarized in Table 2. From the table, it is inferred that both MRR-1 and MRR-2 increase as T_{ON} increases, indicating direct proportionality of the response. Likewise, as T_{ON} increases, the values of R_a -1 and R_a -2 increase, which is not the required criterion, since for R_a , the strategy “smaller the better” is applicable. Similar results were obtained by Pramanik et al. [28], whereby an increase in T_{ON} directly influenced the

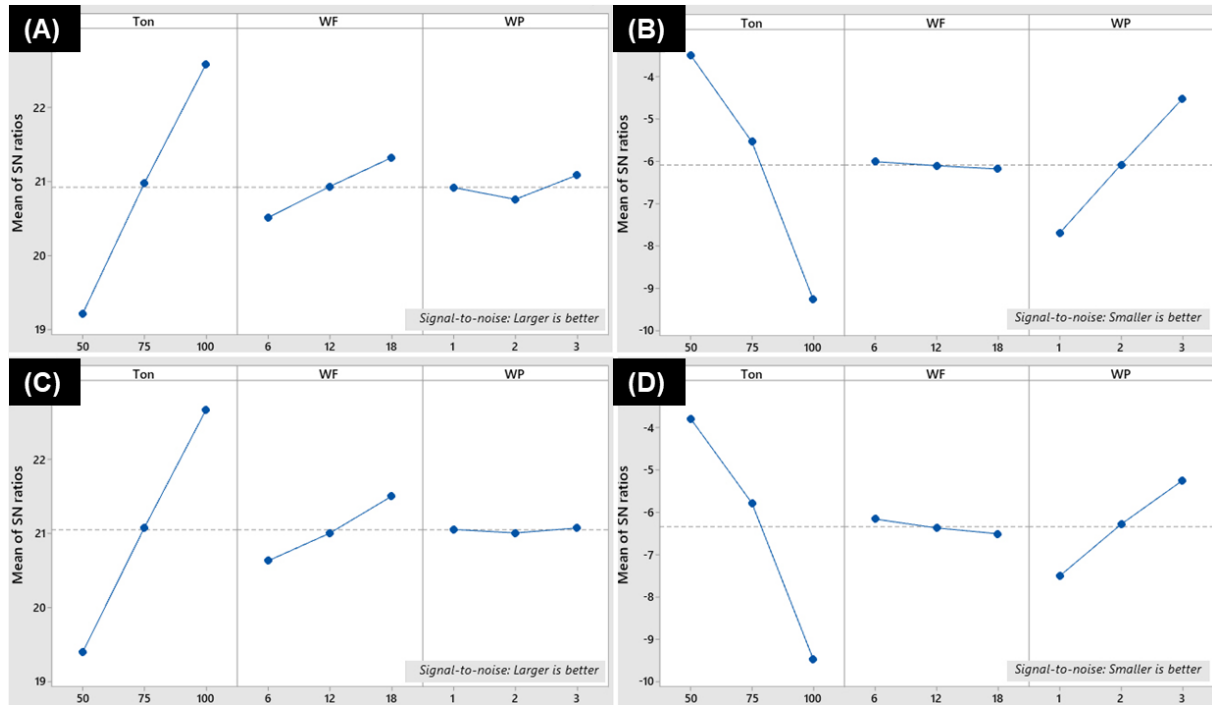


Fig. 3. Influence of the input factors on the S/N ratio of (A) MRR-1, (B) R_a -1, (C) MRR-2, and (D) R_a -2. MRR-1, material removal rate; R_a , surface roughness; S/N, signal-to-noise

MRR but had a negative impact on R_a . As T_{ON} increases, the machining time increases, leading to higher MRR. In contrast, high T_{ON} leads to the generation of large thermal energy, resulting in a large crater and this causes the R_a to increase. MRR-1 and MRR-2 display the same trend for the increase in WF rate as that of T_{ON} , indicating that higher WF rate is essential for good MRR. Kapoor et al. [29] also obtained the same results, whereby the MRR increased with WF rate. However, the values of both R_a s do not tend to have a particular proportionality with the increase in WF rate. This fact is attributed to the interference by the parameter FP, whereby the machining debris is easily removed if the FP is higher, resulting in a reduced R_a value. Therefore, all the parameters are intertwined with each other, and the most influential parameters can be predicted using the signal-to-noise (S/N) ratios for all the responses.

Figures 3A–3D display the influence of the input parameters on the S/N ratios of MRR-1, R_a -1, MRR-2, and R_a -2, respectively, where the strategy “larger is better” is applied for MRRs and “smaller

is better” is applied for R_a s. From Figure 3A, it is inferred that MRR-1 is influenced by the input parameters in the order $T_{ON} > \text{WF rate} > \text{FP}$. Likewise, the S/N ratios of MRR-2 also display the same pattern of parameter influence (Figure 3C). As the T_{ON} is increased, the heat generated due to the electrical discharge becomes high, leading to the melting and evaporation of the base metal, constituting better MRR. Following T_{ON} , the WF rate influences the WEDM process to yield better MRR. During the WEDM process, the electrical discharge from the machining wire tends to remove the materials, making the space vacant. Therefore, for continuous machining, the wire is fed along the direction of machining. Hence, the WF rate constitutes an important parameter for MRRs, whereby a low rate may cause dampened MRR and a high rate may hinder the machining performance. The dielectric medium (parameter FP) is used to keep the temperature under control and remove all the debris from the machining area. Therefore, its pressure determines how far the temperature is controlled and how well the debris is removed. For MRR-1

Table 3. ANOVA for MRR-1, R_a -1, MRR-2, and R_a -2

Response	Source	DF	Adj. SS	F-value	P-value
MRR-1 $R^2 = 99.65\%$	T_{ON}	2	27.9286	268.49	0.004
	WF	2	1.4216	13.67	0.068
	FP	2	0.1940	1.87	0.349
	Error	2	0.1040		
	Total	8	29.6483		
R_a -1 $R^2 = 96.64\%$	T_{ON}	2	3.07616	22.98	0.042
	WF	2	0.05429	0.41	0.712
	FP	2	0.72142	5.39	0.157
	Error	2	0.13389		
	Total	8	3.98576		
MRR-2 $R^2 = 97.82\%$	T_{ON}	2	27.4332	1818.10	0.001
	WF	2	1.8955	125.62	0.008
	FP	2	0.0138	0.91	0.523
	Error	2	0.0151		
	Total	8	29.3575		
R_a -2 $R^2 = 96.26\%$	T_{ON}	2	3.19647	22.69	0.042
	WF	2	0.05627	0.40	0.715
	FP	2	0.37520	2.66	0.273
	Error	2	0.14087		
	Total	8	3.76880		

Adj., adjusted; ANOVA, analysis of variance; DF, degrees of freedom; F , F -ratio; FP, flushing pressure; MRR-1, material removal rate-1; P , probability; R_a , surface roughness; SS, sums of squares; T_{ON} , pulse on time; WF, wire feed.

and MRR-2, the parameter FP displays the least influence, validating that not much temperature difference is caused due to different FPs. Further, the debris removal process does not have a significant effect on the MRR. Figures 3B and 3D show the effect of the input parameters on the S/N ratio of R_a -1 and R_a -2, respectively. For both R_a s, the input parameters that influence the S/N ratio are in the order $T_{ON} > FP > WF$ rate. It is obvious that as T_{ON} increases, the MRR increases, leading to high R_a . However, for better machining performance, the R_a should be minimum, and therefore, high T_{ON} has a negative impact on R_a . Unlike the S/N ratio of MRR, FP has a significant impact on R_a . This may be due to the efficient removal of debris from the machining area with high FP. If the debris is not removed efficiently, the debris itself melts during the WEDM process, forms a layer over the machined surface, and solidifies, constituting a recast layer. This recast layer will not be a smoothened surface but is rough, which tends to increase the R_a value of the machined surface. Therefore, as the FP in-

creases, the R_a tends to reduce. R_a is least affected by the WF rate. However, a high WF rate constitutes high MRR and should result in a high R_a . But, due to the influence of FP, the influence of the WF rate becomes a combined effect.

The analysis of variance (ANOVA) for the responses MRR-1, R_a -1, MRR-2, and R_a -2 are summarized in Table 3. For MRR-1 and MRR-2, the input parameter T_{ON} contributed significantly, i.e., 94.2% and 93.4%. Following T_{ON} , the WF rate showed 4.8% and 6.5% contribution toward MRR-1 and MRR-2, respectively; FP was the insignificant parameter, as presented in the above discussion. In all the cases, the error was $< 5\%$, and therefore, the confidence level is $> 95\%$. From Table 2, it is inferred that the process parameters with high T_{ON} (100 μ s) and WF rate (18 m/min) display high MRR-1 (3.61 mm³/min) and MRR-2 (14.13 mm³/min). For R_a -1 and R_a -2, the input parameter T_{ON} contributed 77.1% and 84.8%, respectively. The FP influences the R_a more than the WF rate, contributing 18.1% and 10% for R_a -1 and R_a -2, re-

spectively. For the R_a s, the WF rate has the least significant contribution. From Table 2, it is to be noted that R_{a-1} (1.11 μm) and R_{a-2} (1.24 μm) have the least value when T_{ON} is the least (50 μs) and FP is the highest (3 MPa). Here, the WF rate is found to be the highest (18 m/min) but does not have a significant contribution. Therefore, the input parameter FP is insignificant to the response MRR although displaying a significant effect on R_a .

The response function for the responses influenced by the input parameters is compiled and is expressed as follows:

$$\begin{aligned} MRR1 = 3.722 + 0.08627 T_{ON} \\ + 0.0811 WF + 0.052 FP \end{aligned} \quad (6)$$

$$\begin{aligned} MRR2 = 3.989 + 0.08547 T_{ON} \\ + 0.09333 WF - 0.0450 FP \end{aligned} \quad (7)$$

$$\begin{aligned} R_{a1} = 0.541 + 0.02780 T_{ON} \\ + 0.0158 WF - 0.347 FP \end{aligned} \quad (8)$$

$$\begin{aligned} R_{a2} = 0.352 + 0.02833 T_{ON} \\ + 0.0161 WF - 0.250 FP \end{aligned} \quad (9)$$

The predicted values are comparable to the experimental values, with marginal errors (Supporting Information, Figure S1). From these data, it is clear that for high MRR, Level 3 of T_{ON} and Level 3 of WF rate are required, and for low R_a , Level 1 of T_{ON} and Level 3 of FP are required. Therefore, selecting the set of optimal parameters without compromising both MRR and R_a is a tedious task.

Grey relational analysis is a technique that measures the performance of the set of parameters as per the responses. Generally, grey relational analysis is performed when there are >1 responses. As per the formulas presented in Section 2.3, the normalized values, grey relational coefficient, and GRGs are computed for the WEDM process of both AA6063/SiC_b and AA6063/SiC_g and are tabulated in Tables 4 and 5. For evaluating normalized data for MRRs, the formula “higher the better” is utilized, whereas for R_a , the formula “smaller the better” is used. The grey relational coefficient

is calculated using the normalized data and consequently, GRGs are computed using the grey relational coefficient. The GRGs use the influence of both the responses, i.e., MRR and R_a . The ranks are allotted as per the grades, whereby higher the grade values, better is the rank for each set of processing parameters. From Tables 4 and 5, it is clear that for both the experimental schemes, the parameters $T_{ON} = 50 \mu\text{s}$, WF rate = 18 m/min, and FP = 3 MPa display the highest GRG, i.e., Rank 1, with the responses as follows: MRR-1 = 9.78 mm³/min, R_{a-1} = 1.11 μm , MRR-2 = 9.94 mm³/min, and R_{a-2} = 1.24 μm . Here, to obtain an optimal machining performance, T_{ON} is found to be the least of the set values, whereas the WF rate and FP are the highest. If the T_{ON} increases, the MRR increases drastically, which leads to the formation of more recast layers, resulting in a high R_a [30]. Likewise, WF rate is also directly proportional to MRR, but the optimum WF rate is found to be high, probably to cope with the reduced value set for T_{ON} . The FP value is the highest of the set levels, which is required to flush the machined debris from the working site [31]. Furthermore, optimum FP restricts the buildup of heat on the working sample, which avoids the fusion of melted debris over the samples, which may in turn affect the overall machining process.

Both AA6063/SiC_b and AA6063/SiC_g are found to have comparable MRR and R_a values, owing to the presence of the same matrix material. However, AA6063/SiC_g has a slightly higher value, probably attributed to the influence of SiC_g, which is more brittle than SiC_b. Therefore, SiC_g is easily removed during the WEDM process, leading to higher MRR. Subsequently, the R_a also increases due to the high MRR. These facts can be validated by recording the surface morphology of the machined surface. Figures 4A and 4B show the SEM micrographs of the WEDM-processed surface of AA6063/SiC_b. Here, the laminate-like structures are the recast layers of removed or melted AA6063/SiC_b, where the size of the grains is higher, compared to the grain size of AA6063/SiC_g (Figures 4C and 4D). The recast layer is formed due to the inefficient flushing of the debris during the WEDM process. The mate-

Table 4. Grey relational analysis for the WEDM process of AA6063/SiC_b

Experimental data		Normalized data		Grey relational coefficients		GRG-1	Rank
MRR-1	R _a -1	MRR-1	R _a -1	MRR-1	R _a -1		
8.57	1.88	0	0.613	0.333	0.564	0.449	9
9.09	1.59	0.103	0.759	0.358	0.675	0.516	7
9.78	1.11	0.240	1.000	0.397	1.000	0.698	1
10.51	1.65	0.385	0.729	0.448	0.648	0.548	6
11.23	1.67	0.528	0.719	0.514	0.640	0.577	5
11.86	2.45	0.653	0.327	0.590	0.426	0.508	8
13.25	2.56	0.929	0.271	0.875	0.407	0.641	4
13.52	3.09	0.982	0.005	0.966	0.334	0.650	3
13.61	3.10	1.000	0.000	1.000	0.333	0.667	2

GRG, grey relational grade; MRR-1, material removal rate-1; R_a, surface roughness; WEDM, wire-cut electrical discharge machining.

Table 5. Grey relational analysis for the WEDM process of AA6063/SiC_g

Experimental data		Normalized data		Grey relational coefficients		GRG-1	Rank
MRR-2	R _a -2	MRR-2	R _a -2	MRR-2	R _a -2		
8.81	1.82	0	0.699	0.333	0.625	0.479	9
9.27	1.63	0.086	0.798	0.354	0.712	0.533	7
9.94	1.24	0.212	1.000	0.388	1.000	0.694	1
10.83	1.69	0.379	0.767	0.446	0.682	0.564	4
11.19	1.81	0.447	0.705	0.475	0.629	0.552	6
11.98	2.40	0.596	0.399	0.553	0.454	0.504	8
13.05	2.72	0.797	0.233	0.711	0.395	0.553	5
13.66	3.05	0.912	0.062	0.850	0.348	0.599	3
14.13	3.17	1.000	0.000	1.000	0.333	0.667	2

GRG, grey relational grade; MRR-2, material removal rate-2; R_a, surface roughness; WEDM, wire-cut electrical discharge machining

rial that is removed by melting solidifies to form a recast layer. Even though the FP (3 MPa) is high, the recast layer is formed. However, the grain size of the recast layer is different for AA6063/SiC_b and AA6063/SiC_g due to the influence of the reinforcement material. Due to the brittle nature of SiC_g, they are easily removed. However, while recasting, SiC_g shows a particle-like morphology over the machined surface. In contrast, SiC_b forms a layer over the machined surface, providing a smooth surface. This fact can be further confirmed using the topographical texture of the SEM image computed using Gwyddion image processing software, Jihlava, Czechia. Figures 5i–iii and 5iv–vi show the surface texture profile computed from Figures 4B and 4D, respectively, at three distinct positions. The red arrow mark represents the 100-count po-

sition on the y-axis. From Figure 5, it is clear that the AA6063/SiC_b machined surface has lower-intensity peaks compared to the machined surface of AA6063/SiC_g, due to the influence of the different kinds of SiC particles. Therefore, to impart a smooth surface while machining using WEDM, using SiC_b to reinforce AA6063 provides a better surface finish compared to the use of SiC_g. Likewise, in applications where higher MMR is required, SiC_g can be used as reinforcement to AA6063.

The finish of the machined surfaces of AA6063/SiC_b and AA6063/SiC_g can be further estimated through EDX with mapping analysis. From the Al mapping spectrum of AA6063/SiC_b shown in Figure 6, it is clear that the surface is considerably even. The other elements in the composites such as Mg, SiC, and C are found to have been

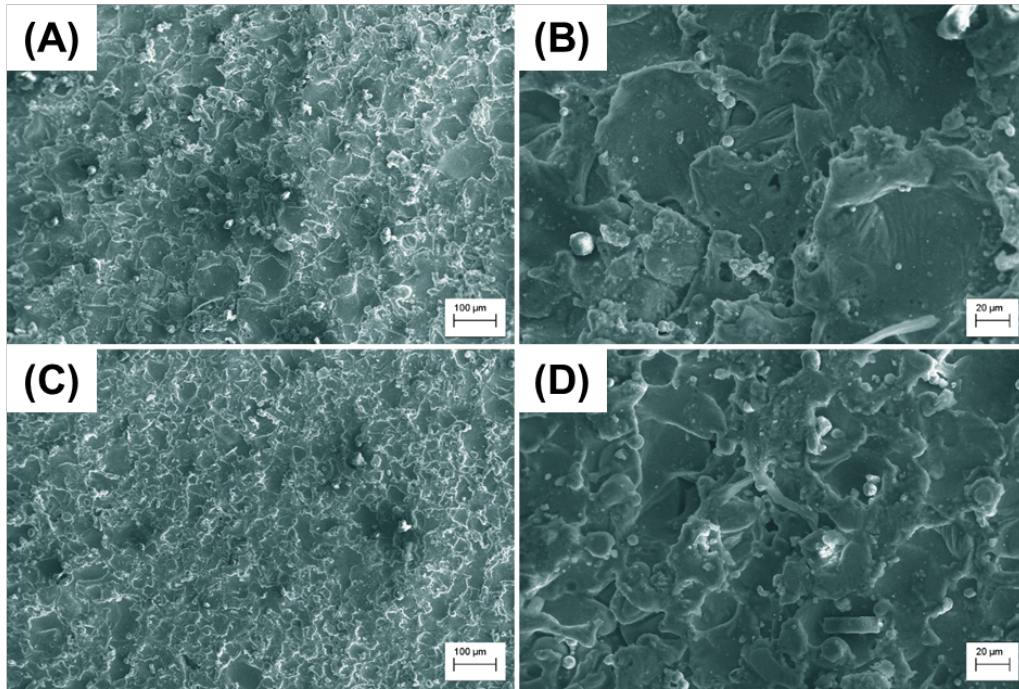


Fig. 4. SEM micrographs of WEDM-processed surfaces: (A, B) AA6063/SiC_b and (C, D) AA6063/SiC_g. SEM, scanning electron microscopy; WEDM, wire-cut electrical discharge machining

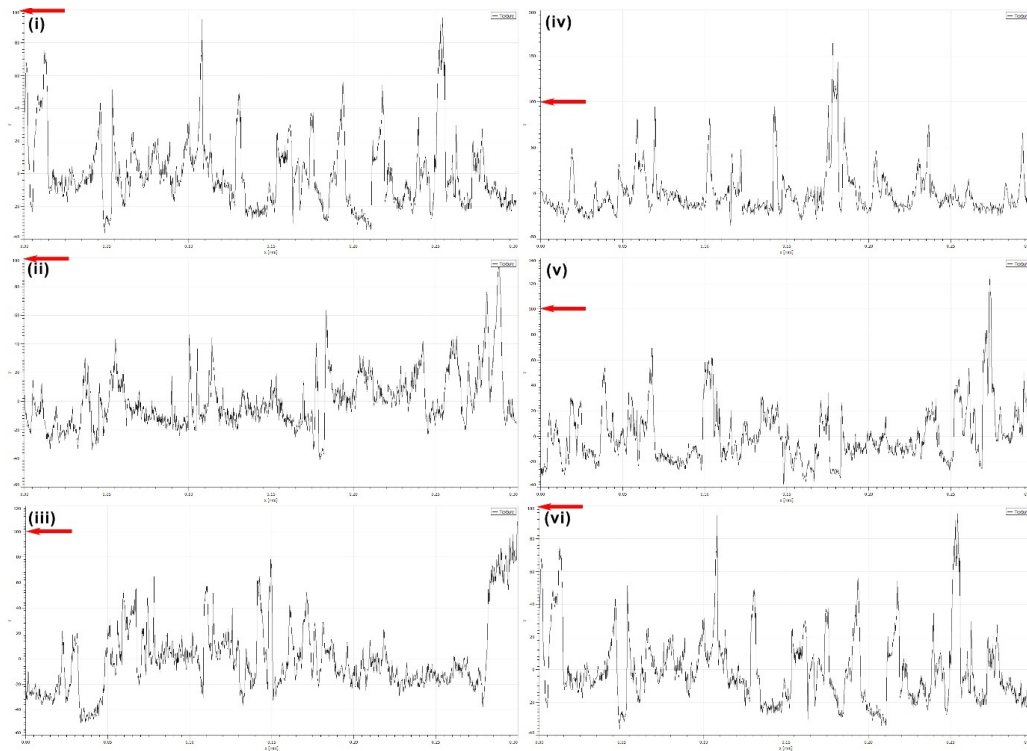


Fig. 5. Texture analysis from Figure 4B (i–iii) and Figure 4D (iv–vi) at three different positions using Gwyddion image processing software (the red arrow denotes the 100-count mark)

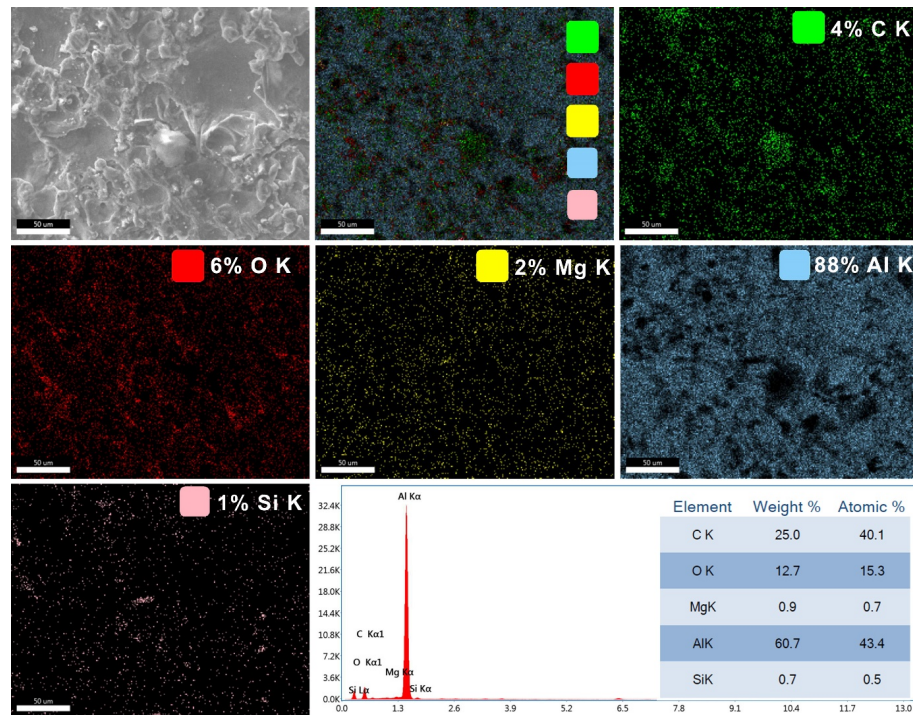


Fig. 6. EDX mapping analysis over the machined surface of AA6063/SiC_b. EDX, energy dispersive X-ray spectroscopy; C, carbon; O, oxygen; Mg, magnesium; Al, aluminium; Si, silicon

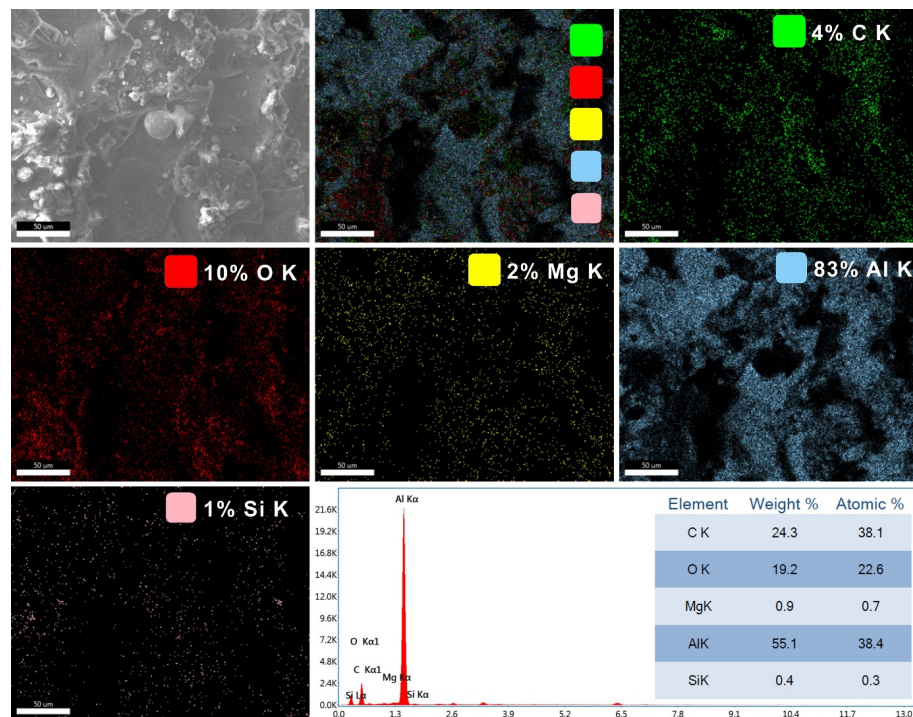


Fig. 7. EDX mapping analysis over the machined surface of AA6063/SiC_g. EDX, energy dispersive X-ray spectroscopy; C, carbon; O, oxygen; Mg, magnesium; Al, aluminium; Si, silicon

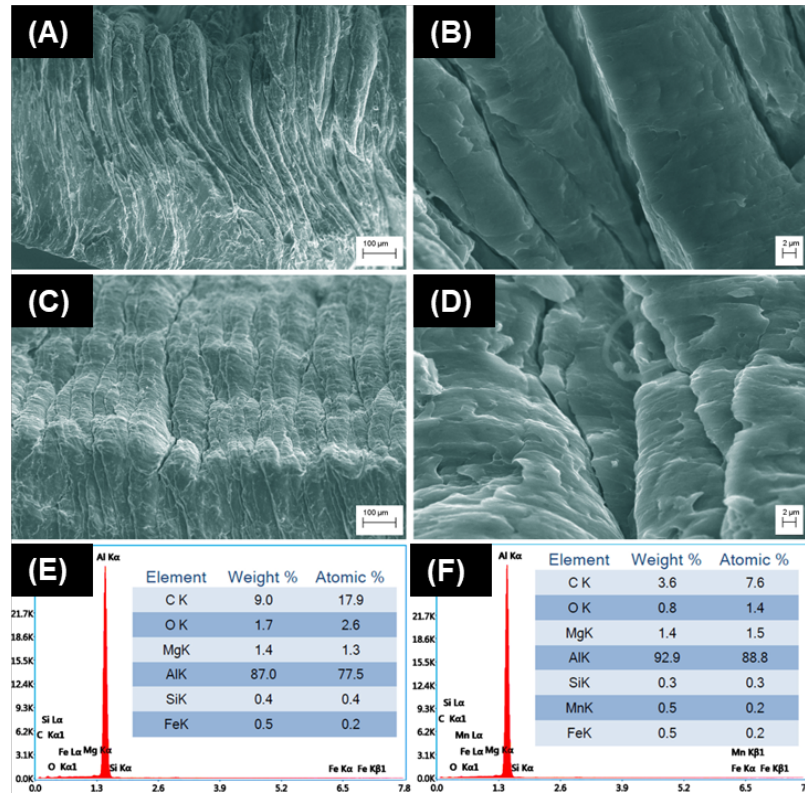


Fig. 8. SEM micrograph of debris generated from (A and B) AA6063/SiC_b and (C and D) AA6063/SiC_g. EDX analysis of debris generated from (E) AA6063/SiC_b and (F) AA6063/SiC_g. EDX, energy dispersive X-ray spectroscopy; SEM, scanning electron microscopy

evenly distributed without any aggregation, resulting in low R_a -1. However, while checking the Al mapping spectrum of AA6063/SiC_b, shown in Figure 7, the surface is not even and has large deformities. Likewise, other elements are also unevenly distributed, showing irregularities in the topography. In both the samples, the presence of O substantiates the fact that metallic oxides are formed during the WEDM process. Another noteworthy feature in Figures 6 and 7 is the higher atomic percentage of C compared to Si. As SiC is used as reinforcement, the atomic percentage should be the same for Si and C. However, from the obtained data, it is clear that the atomic percentage of C is 50 times higher than that of Si. This is due to the fact that C dissociates from SiC during the high-energy WEDM process and is deposited over the surface as a layer. In both the cases, i.e., for AA6063/SiC_b and AA6063/SiC_g, almost the same percentage of C is formed, validating the above statement. From

the EDX mapping results obtained, it is clear that AA6063/SiC_b has lower R_a than AA6063/SiC_g for the optimized set of parameters. Therefore, in conditions where a smooth finish is a prerequisite, AA6063/SiC_b can be used, whereas in conditions where MRR is the major concern, AA6063/SiC_g can be used.

Further, the surface morphology and elemental analysis of debris generated during the WEDM process are recorded and shown in Figures 8A–8F. The images display laminar melt-cast-like structures for both AA6063/SiC_b (Figures 8A and 8B) and AA6063/SiC_g (Figures 8C and 8D), which are fused together due to the high temperature generated during the WEDM process. Moreover, the EDX spectra show the same trend as that of the machined surface, i.e., C is dissociated from SiC, showing a higher atomic percentage of C than of Si (Figures 8E and 8F).

4. Conclusion

AA6063 was reinforced with 10% SiC_b and SiC_g separately using the stir casting technique. The stir casting technique was performed at 850°C, whereby 10 wt.% SiC was dispersed in the molten AA6063 alloy. The machining parameters, such as pulse on time, WF rate, and FP, for the responses such as MRR and surface roughness were optimized for the WEDM process using Taguchi L9 orthogonal array with grey relational analysis. From the GRG, $T_{ON} = 50 \mu s$, WF rate = 18 m/min, and FP = 3 MPa were found to be the optimum set of parameters for better machining performance. Further, confirmation experiments were performed and the machining performances were evaluated using SEM with EDX mapping analysis and texture analysis. From the obtained results, it is clear that while performing the WEDM process, AA6063/SiC_b gives a better surface finish, but AA6063/SiC_g provides a better MRR. Therefore, as per the requirement, SiC grade can be used as reinforcement for AA6063.

Statements and Declarations

There is no financial or nonfinancial conflict of interest in the present research work.

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SUPPORTING INFORMATION

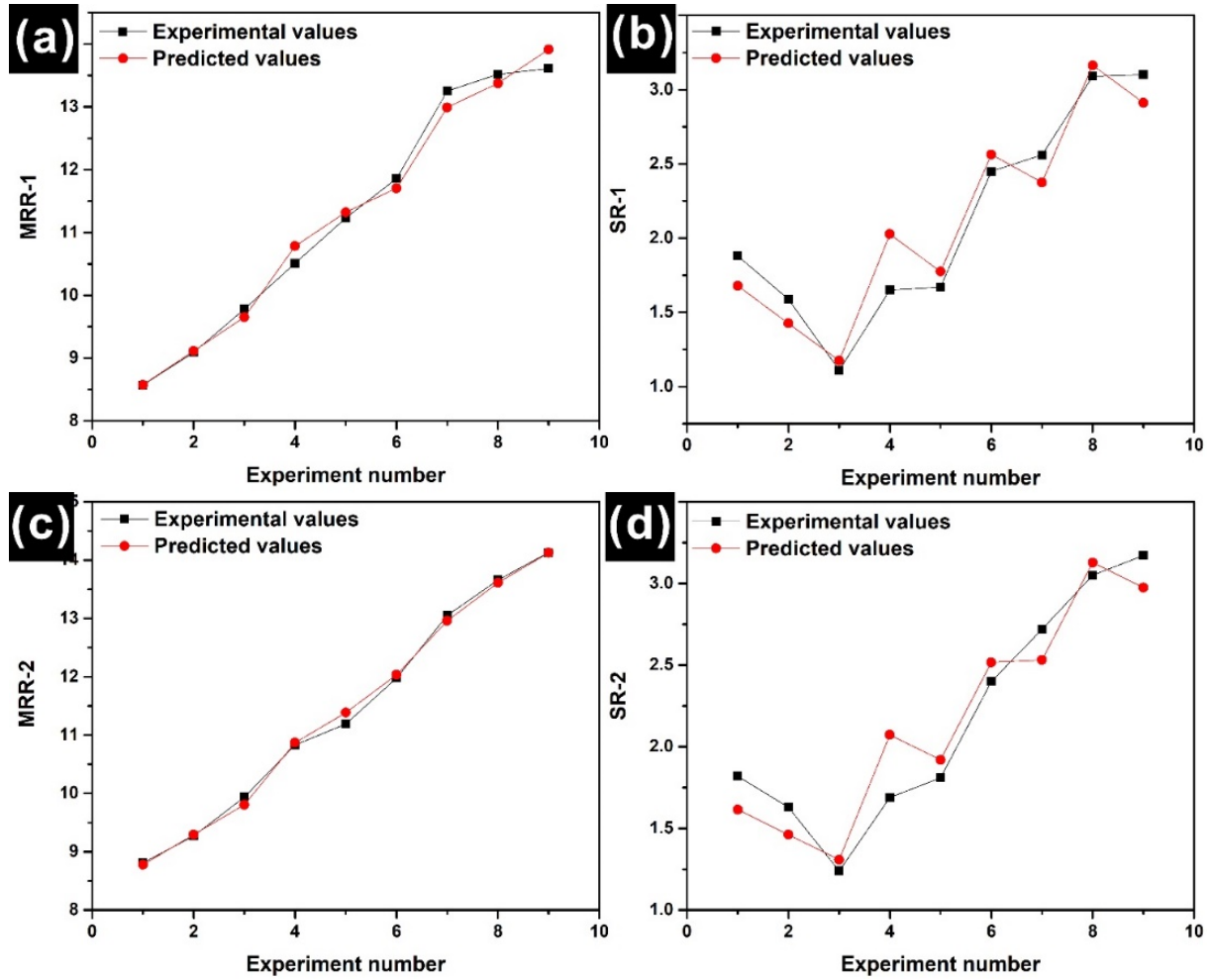


Fig. S1. Experimental vs predicted values for (A) MRR-1, (B) R_a -1, (C) MRR-2, and (D) R_a -2. MRR, material removal rate; R_a , surface roughness