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Research Article

Optimization of AA6351-SiC-B_4C Hybrid Composites in Wire EDM Using Grey Relation Technique

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ABSTRACT

Composite materials are identified to be an alternate solution for the present-day problems pertaining to the reduction of the weight of the components without compromising on their strength and stiffness. The application of the different reinforcements improves the mechanical or thermal properties of the base matrix material related to the application and the heterogeneous nature of the composite material adds flexibility in the design. The manufacturing methods of the composites have also improved in the recent past to ensure that the Reinforcements are properly distributed in the base matrix. Machining a hard composite using conventional techniques is tedious, time-consuming, and will lead to higher tool wear. Therefore, non-conventional machining processes were adopted for the machining of the composite material which can be carried out using inexpensive tooling, The present work aims at optimization of the machining parameters and helps in providing better productivity and cost-effectiveness. The material identified for the optimization was AA6351-SiC-B4C hybrid composites which have widespread application in the nuclear industry. This work aimed at the optimization of the parameters by employing Analysis of Variance (ANOVA) and Response Surface Methodology (RSM) for the identification of the optimum parameters. The current was identified to be the major contributing parameter for the machining of the composite for the output parameters considered. The optimum values for all the composites were identified to be at 12A current.100 µs Pulse on time and feed rate of wire at 8m/min irrespective of the percentage variation of B4C. It can be identified that the optimum values identified are independent of the reinforcement percentage and therefore, can be adopted for all the percentages of B4C in the composite.

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1. Introduction

Composites have been finding their place as a replacement for alloys in the industry due to their improved properties and flexibility. In the current situation, material research is focused on finding lighter materials that can support greater loads. This has ignited a lot of research being carried out on composite materials, which are lightweight and easy to manufacture. The composites also allow quicker development and modification than traditional materials. However, the machining of these composites presents a significant challenge for the researchers, and it is difficult for them to predict the behavior of the developed composite during a particular machining process. For the machining of these materials, it was found that the traditional machining methods consume more time and are expensive due to frequent tool changes, which increases the amount of non-productive time. The non-traditional machining techniques which employ a non-contact machining method were found to be an alternate solution to this problem. The best method for machining them was found to be electric discharge machining (EDM) and wire electric discharge machining (WEDM). This research seeks to shed light on the prediction of the major contributor for WEDM machining of composites with the base matrix as AA6351 alloy. The output parameters evaluated in this work were kerf width as well as surface roughness. The developed model was evaluated by conducting a validation experiment for one of the samples and comparing the experimental result with the result obtained from the model. The AA6351-B4C-based composites are being employed in nuclear plants mainly for control rods as well as radiation protection equipment.

The major works referred to for the current research are summarized in Table 1.

Table 1. Summary of the major referenced journals

Main author	Composite material	Method adopted	Input parameters considered	Output parameters	Outcome
Sureshkumar et al.[1]	Al6351- B_4C-SiC	ANOVA and GRA	Current, Pulse on time, Wire Feed Rate	Kerf width and surface roughness	Current is the major parameter.
Muniappan et al.[3]	Al6061- SiC, Graphite	ANOVA and GRA	Pulse on time, Pulse off time, current, voltage, wire drum speed, wire tension	Kerf width and surface roughness	Pulse on time was identified as the major parameter
Das S et al. [6]	Al6061- B_4C-SiC	Response Surface Methodology and Genetic Algorithm	Pulse on time, Pulse off time, Voltage and Feed rate	Material removal rate and surface roughness	Pulse on time was identified as the major parameter
Sureshkumar [12]	Al6351- B_4C-SiC	SEM image analysis	Current, duty factor, pulse on time, gap voltage	Heat-affected Zone, Surface roughness	The current was identified as the major parameter
Reddy M C [16]	Al- Si	Graph theory and utility Concept, Teaching Learning Based Optimization	Current, pulse on time, pulse off time, voltage, and wire tension	Kerf width, Material removal rate, Surface roughness	The current was identified as the major parameter
Mandal K [21]	Al6061	ANOVA	Pulse on time, Pulse off time, Voltage, and wire tension	Kerf width and surface roughness	Pulse on time was identified as the major parameter
Ishfaq K [29]	Al6061-SiC	Multi-objective Genetic Algorithm	Current, Voltage, Pulse on time	Roughness, Cutting rate, Kerf width	The current was the major parameter for the Kerf width and cutting speed. Pulse on time was the major parameter for Surface roughness

Al7075-Al_2O_3-SiC composites'key machining process characteristics were researched by Lal et al. [2]. The research identified pulse duration as the most important element influencing the major output parameters of the composite. The experimental examination on wire EDM in AA6061 dispersed with B_4C as reinforcement had been carried out by Karabulut et al. [4]. Pulse current, voltage, and tension provided on the wire were taken into consideration as input factors for evaluating R_a. It was discovered that the current was a key factor in determining surface roughness. Two different composites with a base matrix as Al6061 consisting of SiC and SiC-B_4C were the composite samples employed for the machining experiments by Ramesh et al. [5] using wire EDM and EDM using Response surface methodology. The input parameters taken into account were gap voltage, pulse duration, current, and pulse interval. The output variants examined in this work were the MRR and the surface roughness.Al-B_4C composites were the subject of experiments by Ekiciet al. [7] with the goal of optimizing the MRR as well as Ra employing the Taguchi technique. Considered process parameters included wire tension, % of B_4C, the diameter of the EDM wire, pulse duration, and pulse gap. After implementing the Gaussian regression, Ma et al. [8] developed the wolf-pack algorithm to find the ideal choice for machining of Aluminum composite reinforced with SiC using wire EDM. In order to identify variations in the material removal rate and 3D surface properties, the work took into account pulse duration & interval, dielectric pressure, as well as tension on the tool wire as process variables. Garget et al.'s [9] research focused on improving the machining parameters of Al/ZrO_2 composite employing wire EDM machining. To determine the ideal values of the input parameters, various optimization techniques were applied to determine the relationship between output and input parameters, the box-Cox method was used. Shandilya and team [10] optimized the AA6061-SiC MMC machined using wire EDM, considering Servo voltage, pulse duration, pulse interval, and wire feed rate. Material removal rate and kerf breadth were taken into consideration as output characteristics. RSM and ANN were compared to identify a better strategy. Experimental research by Saravanan et al. [11] targeted the important factors that are capable of influencing the MRR along with the surface finish of the experimented material for various TiC reinforcement percentages in wire EDM. The increase in reinforcement and pulse duration was shown to have the greatest impact on the output characteristics. With the input parameters of current, pulse duration, duty factor, and gap voltage, Sureshkumar [13] experimented on AA6351-5%SiC-5%B_4C composite processed using EDM to evaluate the Energy consumption, wear rate of the electrode, and surface roughness. The research determined that all of the output parameters that were investigated had the current as their primary contributing element. To identify the optimum surface roughness and material removal rate, Selva Babu et al. [14] conducted studies on the machining of AA6061 alloy by using wire EDM. It was determined that the current, followed by pulse duration, are the contributing factors affecting both the R_a and MRR. Using the Taguchi approach, Saravanan et al. [15] conducted comprehensive tests in the wire EDM machining of AA6063-TiC composites with varying TiC percentages, currents, and pulse duration. In order to determine the temperature distribution, the researchers also developed an FE model for the same using ANSYS software. The study discovered that, whereas surface roughness rises with increased reinforcement percentage, MRR decreases as reinforcement percentage increases. Experimental work on Al-based composites in which magnesium and MoS_2 had been dispersed in the matrix, was conducted by Modrak et al. [17]. Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) were employed to optimize the work. Investigations on the machining of AA6082 composite with graphene and carbon nanotube reinforcements using wire EDM were conducted by Perla et al. [18]. Investigations were conducted in order to optimize kerf width, MRR, as well as surface roughness. The process parameters identified were the feed rate of the wire, voltage, pulse current, and pulse duration. The contributing parameters of all the output parameters were found to be the pulse duration and the voltage. The Aluminum with Graphene in the form of Nano Platelets (GNP) as reinforcements was the focus of Palanisamy et al.'s [19] work on the assessment of its control parameters using wire EDM machining by applying grey relational analysis and the development of an Adaptive Neuro-Fuzzy Inference System (ANFIS) model to forecast the behavior. For the purpose of creating microchannels in electrical circuits, Sreeraj [20] investigated the machining of AA6351 added with TiO2-based Rutile composite. The study was carried out using the wire EDM technique. Employing the Taguchi method, GRA, and PCA techniques, the work targeted in optimizing the major output parameters by creating a hybrid assessment model. Current, voltage, and wire feed rate were the process parameters taken into account for the work. The main contributor to the output parameters, according to the paper, is current. The model was successfully validated by applying the optimal input parameters with values that were near to the outcomes of the experiments. Karmakar and Maji [22] conducted an extensive review of the research conducted on the latest advancements in wire EDM. According to the review, the major quantum of research has focused on aluminum composites developed with the addition of SiC, B_4C, and Al_2O_3. The review identified that there a numerous areas for research for wire EDM on various composites developed using different transition metals as reinforcements. Wire EDM was used by Muniappan et al. [23,27] to machine various AA6061-SiC-graphite hybrid composite combinations. As input parameters, the work took into account pulse duration, pulse interval, current, servo voltage, wire drum speed, and tension. The kerf width was the evaluated parameter in this work, which identified pulse duration as the major factor affecting the parameter. The machining of AA6063/SiC composite using wire EDM with various SiC percentages was investigated by Balasubramanian et al. [24]. The changes in the evaluation parameters of the kerf width as well as surface roughness were analyzed. The considered process parameters were current, pulse duration, and pulse interval for the research study. The research found that whereas pulse interval significantly affects kerf width control, pulse duration significantly affects surface roughness., Paneer Selvam and Ranjith Kumar [25] optimized the machining of Hastelloy C-276 employing wire EDM process using Genetic Algorithm. This work took into account the process parameters of current, pulse duration, pulse interval, voltage, and wire feed speed. Kerf width, time taken for machining, and surface roughness were the evaluation parameters for the work. The investigation on the wire EDM machining of AA-15%SiC MMC was carried out by Modi et al [26]. The goal of the research work was to optimize the relationship between surface roughness, machine feed rate, and kerf width. It was determined that lower machine feed rates increased kerf width and MRR, but enhanced R_a. Experimental evaluation on the wire EDM machining was done by Amruth Babu and Gurupavan [28] for the AA6061 composite with various compositions of SiC. Current, pulse duration, pulse interval, and feed rate were the control parameters considered for the work. It was concluded that adding SiC to the base alloy caused the surface roughness to decrease. In experimental work, Kashif Ishfaq et al. [30] used wire EDM to machine an AA6061-7.5%SiC composite. The work calculated the inaccuracies brought on by wire lag and vibrations. The impact of the hardness of the composite which is employed as the workpiece in the EDM process has been extensively studied by Marafona and Araujo [31]. It was discovered that the workpiece hardness and associated factors significantly affect the MRR and Ra of the EDM process.

The available literature on the wire EDM machining of composites mostly aims at the evaluation and optimization of the optimum parameters for the specific composites without comparing the values with a different composition of the reinforcements in the composite. The present work targets to identify the parameters and their contributions to the kerf width along with surface roughness of AA6351-SiC-B_4C hybrid composite with varying compositions of B_4C, using ANOVA and RSM methods. The work also aims at finding the optimum parameters and evaluating whether the variations in the reinforcements lead to any variation in the level of the process parameters considered

2. Materials and Methods

The material selected for the analysis was AA6351 reinforced with 5%SiC and 3,6,8% B_4C respectively. The alloy and the B_4C for the manufacturing of the composite were obtained from M/s Coimbatore Metals, Nanjappa Road, Coimbatore. The boron carbide used for the composites has a maximum mesh size of 50μm. The basic material composition of the Al6351 alloy is provided as follows:

Aluminum: 97.5%

Silicon: 1.0%

Manganese: 0.6%

Magnesium: 0.6%

Titanium: 0.2%

Copper:0.1%

The SiC used as the reinforcement was obtained from M/s Carburendum Universal which has a mesh size of 30μm.

The mechanical properties of the composites are tabulated in Table 2.

Table 2. Mechanical Properties of the composites

Percentage of B_4C	Hardness (HB)	Yield strength (MPa)	Tensile Strength (MPa)	Density (kg/m^3)
3% B_4C	69.3	98.54	112.38	2718
6% B_4C	73.1	99.41	123.48	2715
8% B_4C	75.1	102.63	131.54	2710

The manufacturing process employed for the composite was stir casting. Initially, the casting die is preheated to 400°C. Al6351 rod is added into the crucible and kept in the furnace. The base material was heated to the temperature of 850°C to take it above the liquid state. The molten metal is stirred using a stirrer at 700rpm and allowed to cool down slowly. The reinforcements were slowly inducted into the molten metal without stopping the stirring action. 2% Magnesium is also added to the molten composite to enhance its wettability. The molten mixture is poured into the preheated rectangular die of size 200mmx150mmx30mm to obtain the final composite.

The SEM images for the different combinations considered are provided in Figure 1(a) to (c). The proper dispersion of the reinforcement in the grain boundaries can be clearly identified in the images. The EDAX image of the Al6351- 5%SiC- 3%B_4C composite to verify the presence of the constituents is added as Figure 1(d). The presence of the major constituents can be clearly seen in the EDAX image provided. Therefore, the sample can be used for further evaluation representing the evaluation of the composite material.

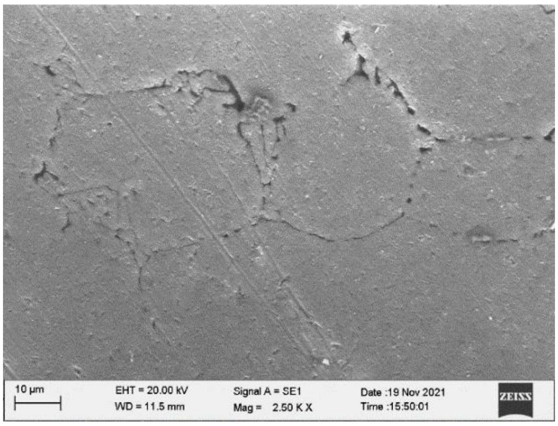

Fig. 1(a). SEM image of Al6351-5%SiC-3%B_4C

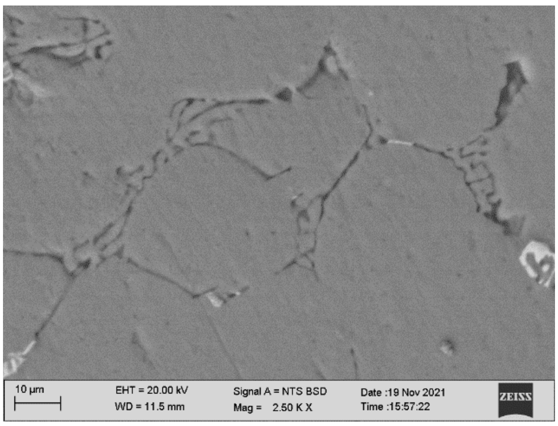

Fig. 1(b). SEM image of Al6351-5%SiC-6%B_4C

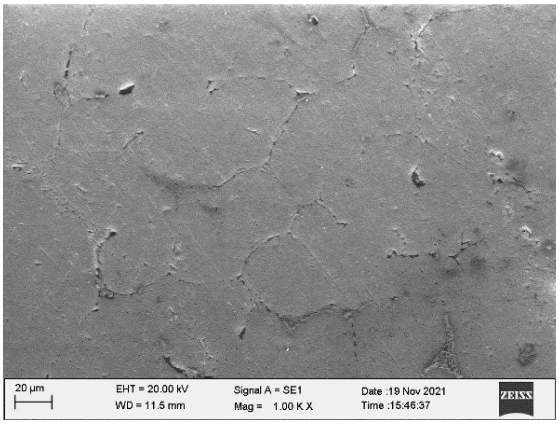

Fig. 1(c). SEM image of Al6351- 5%SiC- 8% B_4C

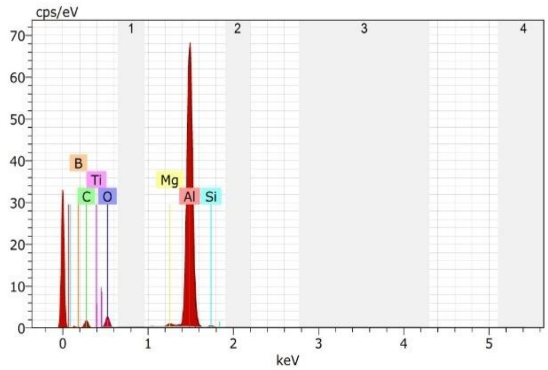

Fig. 1(d). EDAX image of Al6351-5%SiC-3%B_4C

The parameters were fixed based on the previous works in a similar area of research by Sureshkumar et al. [1]. The process parameters identified for the evaluation were current (A), feed rate of the wire (WFR), and Pulse duration (T_{on}). The evaluation parameters considered for the present work were kerf width (KRW) along with surface roughness (R_a). The values of the input parameters are provided in Table 3.

Table 3. Process parameters identified for the experiment

Parameter	Level 1	Level 2	Level 3
Current (A)	12	16	20
Pulse duration (μs)	100	110	120
Feed rate of wire (m/min)	6	8	10

Based on the Taguchi L9 array, 9 experiments each for the different combinations were conducted for identifying the dominating and the predominant parameters for the identification of optimized values of the kerf width along with surface roughness.

The details of the machines and measuring instruments used for the experiment and evaluation were as follows:

Machine:	Wire-EDM (Model:DK7750, M/s Concord United Products Private Limited, Bangalore)
Electrode:	Brass wire (0.25 mm diameter)
Dielectric fluid:	Deionized water
Flushing flow rate:	9 l/min
Surface roughness measuring device:	Mitutoyo,
Model:	Surftest SJ-201
Kerf width measuring device:	Tool makers' microscope

The evaluation of the experimental data was carried out using ANOVA for the identification of the most contributing parameter. The optimum values of the input parameters which are current, pulse-on-time, and feed rate of the wire, were identified for the three different composites using Grey Relation Analysis (GRA). Since the output parameters of surface roughness and kerf width are desired to be minimum, the 'minimum-the-better' condition was applied to both parameters for the optimization of the input parameters. The equation employed for the calculation of the grey relation coefficient is

$$NC = \frac{y_{max} - y_i}{y_{max} - y_{min}}$$

where NC is the normalized value, y_{max} is the maximum observed value of the parameter, y_{min} is the minimum observed value of the parameter, and y_i is the value of the parameter for the corresponding experiment.

3. Results

The experimental output values are provided in Table 4(a), (b) and (c).

Table 4(a). Experimental results- AA6351-5%SiC-3%B_4C

Exp. No	Current (A)	Pulse duration	The feed rate of the wire	Kerf width (mm)	R_a (μm)
1	12	100	6	0.12	5.08
2	12	110	10	0.09	9.584
3	12	120	8	0.1	7.646
4	16	100	6	0.23	5.12
5	16	110	10	0.21	10.68
6	16	120	8	0.22	6.79
7	20	100	6	0.39	5.241
8	20	110	10	0.36	11.98
9	20	120	8	0.38	3.94

Table 4(b). Experimental results- AA6351-5%SiC-6%B_4C

Exp. No	Current (A)	Pulse duration	The feed rate of the wire	Kerf width (mm)	R_a (μm)
1	12	100	6	0.16	6.08
2	12	110	10	0.18	10.16
3	12	120	8	0.2	7.62
4	16	100	6	0.26	5.89
5	16	110	10	0.28	10.85
6	16	120	8	0.33	7.98
7	20	100	6	0.42	5.24
8	20	110	10	0.48	11.05
9	20	120	8	0.5	5.68

Table 4(c). Experimental results- AA6351-5%SiC-8%B_4C

Exp. No	Current (A)	Pulse duration	The feed rate of the wire	Kerf width (mm)	R_a (µm)
1	12	100	6	0.19	5.038
2	12	110	10	0.15	9.223
3	12	120	8	0.16	7.464
4	16	100	6	0.24	4.93
5	16	110	10	0.23	10.775
6	16	120	8	0.28	7.68
7	20	100	6	0.34	5.627
8	20	110	10	0.35	10.54
9	20	120	8	0.38	4.715

The experimental data was analyzed using ANOVA for the different percentages of B_4C. ANOVA is a statistical tool employed for the evaluation of the experimental results to identify the most dominating input parameter. The details of the ANOVA for the kerf width are provided from Table 5 to Table 7.

It can be identified from the ANOVA that pulse current is the significant contributor to the kerf width followed by the Feed rate.

Table 5. ANOVA for Kerf width - AA6351 with 5%SiC-3%B_4C

Parameter	DF	Seq. The sum of Squares (SS)	Contribution	Adj SS	Adj MS
Regression	6	0.113967	99.97%	0.113967	0.018994
A	1	0.112067	98.30%	0.000045	0.000045
T_{on}	1	0.000267	0.23%	0.000032	0.000032
WFR	1	0.000800	0.70%	0.000008	0.000008
A×A	1	0.000800	0.70%	0.000800	0.000800
A×T_{on}	1	0.000025	0.02%	0.000033	0.000033
A×WFR	1	0.000008	0.01%	0.000008	0.000008
Error	2	0.000033	0.03%	0.000033	0.000017
Total	8	0.114000	100.00%		
Standard deviation	0.119				

Table 6. ANOVA for Kerf width - AA6351 with 5%SiC-6%B_4C

Parameter	DF	Seq. The sum of Squares (SS)	Contribution	Adj SS	Adj MS
Regression	6	0.132044	99.76%	0.132044	0.022007
A	1	0.123267	93.13%	0.000790z	0.000790
Ton	1	0.006017	4.55%	0.000004	0.000004
WFR	1	0.000006	0.00%	0.000118	0.000118
A×A	1	0.002222	1.68%	0.002222	0.002222
A×Ton	1	0.000400	0.30%	0.000133	0.000133
A×WFR	1	0.000133	0.10%	0.000133	0.000133
Error	2	0.000311	0.24%	0.000311	0.000156
Total	8	0.132356	100.00%		
Standard deviation	0.129				

Table 7. ANOVA for Kerf width - AA6351 with 5%SiC-8%B_4C

Parameter	DF	Seq. The sum of Squares (SS)	Contribution	Adj SS	Adj MS
Regression	6	0.057078	99.17%	0.057078	0.009513
A	1	0.054150	94.08%	0.000532	0.000532
Ton	1	0.000417	0.72%	0.000356	0.000356
WFR	1	0.000939	1.63%	0.000214	0.000214
A×A	1	0.000272	0.47%	0.000272	0.000272
A×Ton	1	0.001225	2.13%	0.000675	0.000675
A×WFR	1	0.000075	0.13%	0.000075	0.000075
Error	2	0.000478	0.83%	0.000478	0.000239
Total	8	0.057556	100.00%		
Standard deviation	0.129				

The regression equation obtained for the different combinations is as follows:

For AA6351- 5%SiC- 3 % B_4C –

$$KRW = 0.162 - 0.01333\,A - 0.001333\,T_{on} - 0.00333\,WFR + 0.001250\,A^2 + 0.000083\,A{\times}T_{on} - 0.0002\,A{\times}WFR \quad (1)$$

For AA6351- 5%SiC- 6 % B_4C

$$KRW = 0.303 - 0.0558\,A + 0.00044\,T_{on} - 0.0128\,WFR + 0.002083\,A^2 + 0.000167\,A{\times}T_{on} + 0.000833\,A{\times}WFR \quad (2)$$

For AA6351- 5%SiC- 8% B_4C –

$$KRW = 0.683 - 0.046\,A - 0.004\,T_{on} - 0.017\,WFR + 0.0007\,A^2 + 0.0004\,A{\times}T_{on} + 0.0006\,A{\times}WFR \quad (3)$$

The ANOVA for the kerf width clearly indicates that the current is the major contributor to the kerf width as observed by Sureshkumar [1,12] and Reddy [16]. The percentage of contribution by current also shows a constant trend as observed in the referred works irrespective of the variation in the percentage of reinforcements.

The ANOVA analysis conducted for the surface roughness of the different composites is depicted in Table 8 to Table 10.

The feed rate of the wire was identified as the dominating factor for the surface roughness (R_a) as observed from the ANOVA.

Table 8. ANOVA for R_a - AA6351 with 5%SiC-3%B_4C

Parameter	DF	Seq. The sum of Squares (SS)	Contribution	Adj SS	Adj MS
Regression	6	63.6102	99.21%	63.6102	10.6017
A	1	0.2200	0.34%	3.4703	3.4703
Ton	1	1.4357	2.24%	5.3097	5.3097
WFR	1	52.2617	81.51%	0.8321	0.8321
A×A	1	0.1623	0.25%	0.1623	0.1623
A×Ton	1	3.7384	5.83%	8.2817	8.2817
A×WFR	1	5.7921	9.03%	5.7921	5.7921
Error	2	0.5084	0.79%	0.5084	0.2542
Total	8	64.1187	100.00%		
Standard deviation	2.831				

Table 9. ANOVA for R_a - AA6351 with 5%SiC-6%B_4C

Parameter	DF	Seq. The sum of Squares (SS)	Contribution	Adj SS	Adj MS
Regression	6	42.6097	98.77%	42.6097	7.10162
A	1	0.5953	1.38%	1.1882	1.18818
Ton	1	2.7608	6.40%	0.6324	0.63244
WFR	1	36.4943	84.59%	0.0067	0.00665
A×A	1	0.7240	1.68%	0.7240	0.72401
A×Ton	1	0.3025	0.70%	1.2871	1.28707
A×WFR	1	1.7328	4.02%	1.7328	1.73280
Error	2	0.5305	1.23%	0.5305	0.26527
Total	8	43.1403	100.00%		
Standard deviation	2.322				

Table 10. ANOVA for R_a - AA6351 with 5%SiC-8%B_4C

Parameter	DF	Seq. The sum of Squares (SS)	Contribution	Adj SS	Adj MS
Regression	6	45.2838	97.08%	45.2838	7.54730
A	1	0.1184	0.25%	3.9462	3.94617
Ton	1	3.0303	6.50%	3.2104	3.21041
WFR	1	36.4715	78.19%	0.0219	0.02194
A×A	1	0.9628	2.06%	0.9628	0.96281
A×Ton	1	2.7856	5.97%	4.5683	4.56827
A×WFR	1	1.9152	4.11%	1.9152	1.91520
Error	2	1.3639	2.92%	1.3639	0.68194
Total	8	46.6477	100.00%		
Standard deviation	3.308				

The regression equations obtained for the different composites for R_a are as follows:

For AA6351- 5%SiC – 3% B_4C

$$Ra = -47.6 + 3.70\,A + 0.54\,T_{on} - 1.08\,WFR - 0.018\,A^2 - 0.042\,A \times T_{on} + 0.1737\,A \times WFR \quad (4)$$

For AA6351- 5%SiC – 6% B_4C

$$Ra = -20.0 + 2.17\,A + 0.187\,T_{on} - 0.096\,WFR - 0.0376\,A^2 - 0.01637\,A \times T_{on} + 0.0950\,A \times WFR \quad (5)$$

For AA6351- 5%SiC – 8% B_4C

$$Ra = -47.8 + 3.95\,A + 0.422\,T_{on} - 0.175\,WFR - 0.0434\,A^2 - 0.0308\,A \times T_{on} + 0.0999\,A \times WFR \quad (6)$$

The major contributor observed for the surface roughness was found to be the wire feed rate which is a contradictory result from the results observed in the reference journals. The referred journals show current and pulse-on-time as the major contributors to the surface roughness. However, the wire feed rate also had a significant contribution in the referred journals, especially when the hardness of the composite was high.

The Standard deviation depicts the variation levels of the output parameters. It can be observed that the values of standard deviation are high indicating the level of variance in the values obtained is within the normal zone (mean ±2 SD) [32] for all the output values of the experiments when tables 5 to 10 are observed, which indicates that the dispersion of the values in the standard deviation graph is 95.4%. Since the values are not concentrated and have a good variance, these values can be considered for further investigation.

To evaluate the variations in the output parameters based on the input parameter, factorial plots were plotted which are shown in figure 2 to 7. In fig 2 to 4, the factorial plots of the kerf width were plotted and the factorial plots of surface roughness are provided from fig 5 to 7.

It can be observed from the graphs of different compositions that the variations show a similar pattern in different compositions of B_4C in the composite. Therefore, it can be understood that the variation in the percentage of the reinforcement has no effect on the variation pattern for the composite. Both the output parameters are desired to be low. Therefore, optimization needs to be carried out to lower these two parameters.

However, it was observed based on the factorial graphs that the increase of current led to an increased kerf width when it was reducing the surface roughness. The enhancement of Pulse duration time increased the kerf width but reduced the surface roughness. When we consider the wire feed rate, the increase of the parameter decreased the kerf width but increased the surface roughness. Therefore, it can be identified that the input parameters had a conflicting effect on the output parameters. Therefore, the identification of the optimum values for the input parameters requires an additional method to be applied. It was identified from the works in the related areas that, grey relation analysis (GRA) can identify the optimum input parameters.

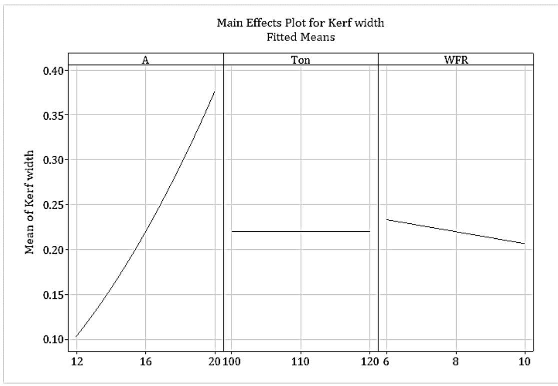

Fig. 2. Factorial plot of kerf width for AA6351-5%SiC-3% B4C

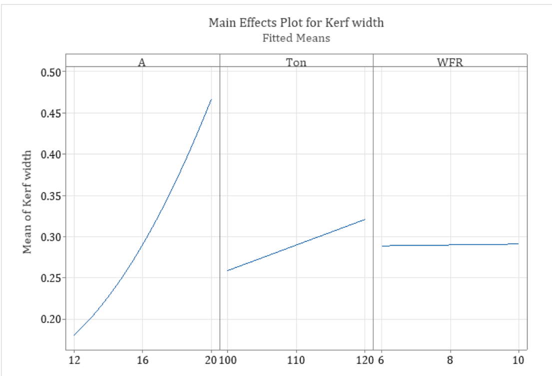

Fig. 3. The factorial plot of kerf width for AA6351-5%SiC-6%B_4C

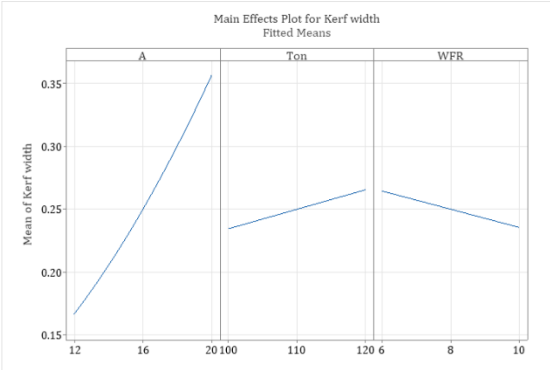

Fig. 4. Factorial plot of kerf width for AA6351-5%SiC-8%B_4C

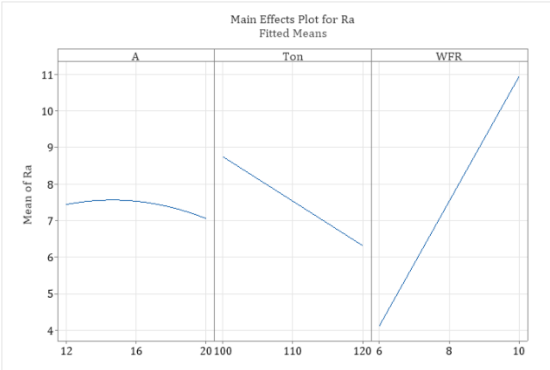

Fig. 5. The factorial plot of surface roughness for AA6351-5%SiC-3% B_4C

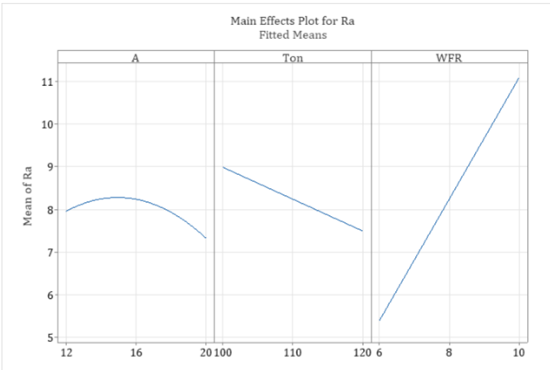

Fig. 6. Factorial plot of surface roughness for AA6351-5%SiC-6% B_4C

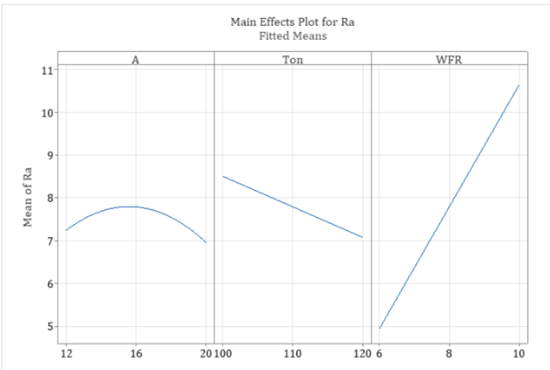

Fig. 7. Factorial plot of surface roughness for AA6351-5%SiC-8% B_4C

Parameters, and based on ‘smaller-the-better condition, the Grey relation analysis details are provided in Table 11 to Table 13 for the different compositions.

Table 11. Grey relation table of AA6351- 5% SiC-3%B_4C

Experiment No.	Normalized values		Deviation		Grey relation coefficient		Grey relation grade	Order
	KRF	Ra	KRF	Ra	KRF	Ra		
1	0.900	0.858	0.100	0.142	0.833	0.779	0.806	1
2	1.000	0.298	0.000	0.702	1.000	0.416	0.708	3
3	0.967	0.539	0.033	0.461	0.938	0.520	0.729	2
4	0.533	0.853	0.467	0.147	0.517	0.773	0.645	5
5	0.600	0.162	0.400	0.838	0.556	0.374	0.465	8
6	0.567	0.646	0.433	0.354	0.536	0.585	0.560	6
7	0.000	0.838	1.000	0.162	0.333	0.755	0.544	7
8	0.100	0.000	0.900	1.000	0.357	0.333	0.345	9
9	0.033	1.000	0.967	0.000	0.341	1.000	0.670	4

Table 12. Grey relation table of AA6351- 5% SiC-6%B_4C

Experiment No	Normalized values		Deviation		Grey relation coefficient		Grey relation Grade	Order
	Kerf width	Ra	Kerf width	Ra	Kerf width	Ra		
1	1.000	0.855	0.000	0.145	1.000	0.776	0.888	1
2	0.941	0.153	0.059	0.847	0.895	0.371	0.633	5
3	0.882	0.590	0.118	0.410	0.810	0.550	0.680	4
4	0.706	0.888	0.294	0.112	0.630	0.817	0.723	2
5	0.647	0.034	0.353	0.966	0.586	0.341	0.464	8
6	0.500	0.528	0.500	0.472	0.500	0.515	0.507	7
7	0.235	1.000	0.765	0.000	0.395	1.000	0.698	3
8	0.059	0.000	0.941	1.000	0.347	0.333	0.340	9
9	0.000	0.924	1.000	0.076	0.333	0.868	0.601	6

Table 13. Grey relation table of AA6351- 5% SiC-8%B_4C

Experiment No	Normalized values		Deviation		Grey relation co-efficient		Grey relation Grade	Order
	Kerf width	Ra	Kerf width	Ra	Kerf width	Ra		
1	0.826	0.947	0.174	0.053	0.742	0.904	0.823	1
2	1.000	0.256	0.000	0.744	1.000	0.402	0.701	4
3	0.957	0.546	0.043	0.454	0.920	0.524	0.722	3
4	0.609	0.965	0.391	0.035	0.561	0.934	0.747	2
5	0.652	0.000	0.348	1.000	0.590	0.333	0.462	8
6	0.435	0.511	0.565	0.489	0.469	0.505	0.487	7
7	0.174	0.850	0.826	0.150	0.377	0.769	0.573	6
8	0.130	0.039	0.870	0.961	0.365	0.342	0.354	9
9	0.000	1.000	1.000	0.000	0.333	1.000	0.667	5

Based on these grades, the response table was created and the details of the obtained table are provided in Tables 14, 15, and 16.

Table 14. Response table of AA6351- 5% SiC-3%B_4C

Parameter	Level 1	Level 2	Level 3	Max-Min
Current	**0.748**	0.557	0.520	0.228
Pulse duration	**0.665**	0.506	0.653	0.159
The feed rate of the wire	0.571	**0.675**	0.579	0.104

Table 15. Response table of AA6351- 5% SiC-6%B_4C

Parameter	Level 1	Level 2	Level 3	Max-Min
Current	**0.733**	0.565	0.546	0.187
Pulse duration	**0.770**	0.479	0.596	0.291
The feed rate of the wire	0.578	**0.652**	0.614	0.074

Table 16. Response table of A6351- 5% SiC-8%B_4C

Parameter	Level 1	Level 2	Level 3	Max - Min
Current	**0.749**	0.565	0.531	0.218
Pulse duration	**0.714**	0.505	0.625	0.209
The feed rate of the wire	0.555	**0.705**	0.586	0.150

The grey relation analysis provided a clear idea of the optimum input parameters for the wire EDM process as all the compositions have provided the same optimum values as 12 A current, 100µs Pulse duration, and 8m/min Feed rate of wire. The values obtained are similar to the values identified by the work of Sureshkumar et al. [1], the only variation observed was in the feed rate of wire, which shows the medium value in the study whereas the referred journal shows it as a lower value. The optimum values obtained were considered for the conduct of the validation experiment carried out in the AA6351- 5%SiC-3%B_4C sample. The result of the validation experiment is provided in Tables 17 and 18.

The values obtained in the validation experiment were compared with the regression equation obtained from ANOVA. The comparison of the values is provided in Table 19.

The validation results obtained show that the identified parameters are repeatable for future optimization.

Table 17. Validation result of Kerf width in AA6351- 5% SiC- 3% B_4C composite

Current	Pulse duration	The feed rate of the wire	Kerf width			Mean/ Standard deviation
			Exp 1	Exp2	Exp3	
12	100	8	0.10	0.09	0.10	0.097/ 0.006

Table 18. Validation result of surface roughness in AA6351- 5% SiC- 3% B_4C composite

Current	Pulse duration	The feed rate of the wire	Surface roughness			Mean/ Standard deviation
			Exp 1	Exp2	Exp3	
12	100	8	5.55	5.42	5.62	5.53/0.101

Table 19. Comparison – ANOVA and Experimental results

Parameter	Value- Experiment	Value- ANOVA	% variation
KRW	0.097	0.101	3.96
R_a	5.53	5.776	4.26

3.1. Discussion of the Results

The ANOVA identified currently to be the major contributing factor for the kerf width. A similar pattern was observed in the previous works employing AA6351-based composites reinforced with B_4C. The addition of B_4C increases the hardness, which can be a major reason for the domination of current in the variation of kerf width. The higher current with a constant voltage implies a higher spark energy which leads to the increase in the Kerfwidth. The response table clearly indicates that a lower current reduces the kerf width which is desirable while machining precise components like in the nuclear industry.

The surface roughness has been identified to be dominated by the wire feed rate when the ANOVA tables pertaining to the R_a are verified. The domination of the wire feed rate can be attributed to the fact that the spark distribution on the machined surface will be more uniform for a medium wire feed rate which will improve the surface finish. The lower wire feed rate may lead to concentrated spark erosion occurring in a specific zone, thereby increasing the surface roughness. A lower surface roughness can be obtained due to a proper distribution of the spark from the wire to the workpiece. The response table also indicates that the medium level of the feed rate of the wire would provide the optimum output for the machining.

3.2. Comparison with Previous Works

The previous literature by Sureshkumar [1,12], Reddy [16], and Ishfaq[29] for similar composites also identified current as the major contributor to the kerf width which can be confirmed based on the results obtained from the present work. However, the works of Muniappan [3], Das [6], and Mandal[21] identified pulse-on-time as the major contributor to the kerf width. The variation in the contribution can be attributed to the fact that the Al6061 is a softer alloy when compared to Al6351 and the contribution of reinforcements, especially graphite reduces the hardness of the composite. Lower hardness composites depend more on pulse-on-time when compared to current as the electrical energy required for the removal of material from the workpiece will be lower for a low hardness composite.

For the surface roughness, the Wire feed rate was identified to be the major contributor in the present work. The previous works by Sureshkumar [1,12] identified current as the major contributor and Muniappan[3], Das [6], Reddy [16] as well as Mandal [21] identified pulse on time as the major contributor in surface roughness, which was a conflicting outcome for the existing experimental study. The analysis of the previous works indicates that the contribution of the current increases with the hardness, but there was a noticeable contribution from the wire feed rate in all the previous works. Therefore, it can be identified that the wire feed rate, though at a lower percentage, was also contributing to the surface roughness. The contribution in the present work increased due to the higher hardness of the composite creating a concentrated spark in specific zones, reducing the surface roughness at a lower wire feed rate and more dispersed sparks at a higher feed rate contributed adversely to the surface roughness of the workpiece.

The values identified for the optimization of the output parameters were also found to be similar to the values obtained by Sureshkumar [1] except for the feed rate of the wire which showed a lower value.

Based on the previous works related to the present work, it can be clearly identified that the value of kerf width is dominated by current irrespective of the percentage of reinforcements added to the matrix material. The higher influence of the wire feed rate in the present experimental setup can be attributed to the presence of a higher percentage of reinforcements in the base matrix. The works referred to also had a comparable contribution to the wire feed rate in the experimental works.

4. Conclusions

The optimized condition for the machining of AA6351-SiC-B_4C hybrid composites was identified using ANOVA and Grey relation analysis (GRA).

- Based on ANOVA and the factorial plots, it was recognized that the current is the major process factor for variation in kerf width. The kerf width was observed to increase when the input current was increased. The increase in kerf width due to the increase in current can be identified to be due to the increased energy during the operation which removes more material from the workpiece.
- Based on the ANOVA and the factorial plots, it was observed that the surface roughness is mainly controlled by the feed rate of the wire and the higher feed rate of the wire increased the surface roughness. The increased feed rate of wire distributes the spark on a larger area increasing the surface roughness and a reduced feed rate of wire will be a better option for a better surface finish.

- The Grey relation analysis results show that for an optimized condition of the conflicting parameters of kerf width and surface roughness, the current and the Pulse duration should be kept at the lower level and a medium Feed rate of wire should be preferred.
- The optimum conditions for the parameters were identified as Current – 12 A, Pulse duration – 100µs, and Feed rate of wire – 8m/min.
- It can also be observed that the optimum values of the input parameters are not changing with variation in the percentage of B_4C. Therefore, it can be concluded that the present optimum values can be employed for varying percentages of B_4C in the Al6351 matrix.

The present work can be increased to higher reinforcements using the squeeze casting manufacturing method and the accurate prediction of the results using modeling can be targeted using Artificial Intelligence techniques.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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