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ASSESSMENT OF CORROSION PERFORMANCE OF HYBRID-AL-B4C-RM COMPOSITES THROUGH TAGUCHI TECHNIQUE

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Abstract

The corrosion performance of aluminium-based hybrid composites, incorporating Boron carbide (B4C) and red-mud (RM) reinforcements, was explored using the Taguchi method in this analysis. The procedure employed to build composites with varying weight percentages of B4C and a consistent RM involved the application of stir casting. The corrosion performance of the composites was examined to investigate the influences of B4C weight percentage, solution normality, and immersion duration in an HCl solution. The specimens underwent testing in HCl solutions with normality values of 0.25, 0.5, 0.75 and 1, and were exposed for a period ranging from 24 to 96 hours. By utilising the design of experiments method and the Taguchi technique, the statistical analysis of the composites' corrosion characteristics was conducted. The corrosion behaviour of composites was investigated by employing signal-to-noise ratio and analysis of variance techniques to examine the impacts of different parameters. The outcomes demonstrated that the composites outperformed the monolithic alloy AL-6061 in terms of corrosion resistance. The corrosion rate and weight loss were significantly influenced by the solution normality, immersion duration, and percentage of reinforcement. Scanning electron microscopy serves to investigate the corrosion morphology.

Keywords: AL-6061· Stir casting · Immersion Corrosion · Hybrid Metal Matrix Composites Design of experiments · Taguchi Procedure.

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1 Introduction

The automotive industry frequently employs the Aluminium 6061 alloy because of its desirable blend of characteristics, including good strength, corrosion resistance, and machinability[1]. One of the primary limitations of aluminium-based materials is their inferior hot hardness and wear resistance. The pursuit of metal matrix composites stems from the desire to achieve exceptional mechanical properties and unique combinations of characteristics that aren't often exhibited by traditional engineering materials [2]. The outstanding strength, stiffness, and resistance to wear, high temperatures, and corrosion make metal matrix composites (MMCs) highly valued in diverse industries such as aviation, automotive, and marine sectors[3]. The features of the reinforcement, the amount and dispersal of the reinforcement, and the matrix can all be changed to alter the traits of a composite[4]. Manipulating the reinforcement along with the matrix properties and controlling their relative proportions, enables the creation of novel materials with exclusive property combinations that cannot be found in conventional engineering materials[5].

The targeted properties were achieved in the composite by incorporating one or more reinforced particles. The advancement and utilization of hybrid composite materials are driven by the aspiration to fabricate innovative materials that exhibit distinctive chemical and physical characteristics not seen in conventional engineering materials.

This is achieved by combining various materials to make a new composite with enhanced properties[6][7], for instance Al_2O_3, TiC, B_4C, Fe, and red mud, etc [8][9]. Various manufacturing techniques are accessible for the production of MMCs, including spray casting, stir casting, squeeze casting, and powder metallurgy [10][11][12].

The primary concern when it comes to Aluminium alloys is their high susceptibility to corrosion, particularly due to galvanic corrosion between the metallic alloy matrix and the functionally significant particle or fibre reinforcement. Hence, it's crucial to comprehend the corrosion characteristics of composites in order to ensure suitability for various practical applications [13]. Due to their widespread use in engineering implementations, it is imperative to gain a comprehensive understanding of the corrosion behaviour of HAMMCs (Hybrid Aluminium Metal Matrix Composites). To address these constraints, multiple techniques have been developed, such as employing corrosion-resistant reinforcement materials and applying surface treatments to safeguard the composite against corrosion. The MMCs' rate of corrosion can be impacted by the selection of appropriate matrix and reinforcement material and their composition, size, and distribution.

In three different immersion media, corrosion studies are conducted on composites reinforced with Mg, Graphite-, Ti and B_4C particles. The corrosion resistance of HAMMC's was exceptional to their matrix alloys[14]. The most prevalent corrosion mechanism in composites observed to be pitting[15][16][17], whereas the most prevalent corrosion mechanism in pure aluminium is general attack[18]. In the context of optimizing the factors influencing the corrosion inhibition process, Taguchi orthogonal array of experiments can be applied[19][20].

Despite extensive research performed on the corrosion behaviour of MMCs, the corrosion characteristics of 6061 aluminium-based hybrid aluminium matrix composites (HAMMCs) are still uncertain and insufficiently understood due to a lack of documented research in this area.

The current experiment's goal is to apply the Taguchi technique to perform the corrosion experiments on Boron Carbide-red mud reinforced AL based HMMC's made utilizing stir casting procedure under as-cast conditions with reinforcement contents of 2%, 4% ,6%and 8% B_4C and constant 2% red mud by weight percentages. corrosion assessments were carried out for the test parameters of normality of solution, weight % of B4C, and immersion time. The samples were examined in normal HCL solutions of 0.25, 0.5,0.75 and 1 N with an immersion time of 24, 48 ,72 and 96 hours.

2 Materials and Methods

2.1 Composite Preparation and Experimentation

The purpose of the existing research investigation is to perform corrosion assessments on B4C-RM reinforced aluminium alloys using alloy 6061 as the matrix metal. Table 1 provides the structure of the alloy AL-6061.Boron Carbide of particle sizes ranging from 30-40 µm and red mud particles of 106 µm were selected for the present study. Matrix particles were heated in an electric oven prior to incorporating molten aluminium. To create composites, different amounts of b4c (2%, 4%, 6%and 8%wt) and constant red mud (2% wt.) were mixed with the AL-6061 matrix alloy.

Table 1: Chemical Structure of AL-6061alloy

Element	Mg	Si	Fe	Mn	Cu	Al
Wt%	0.8-1.2	0.4 -0.8	0.7 max	0.15	0.15-0.40	Balance

The stir casting procedure was adopted to develop the Al/B4C/RM hybrid composite materials. Stir casting is a method of manufacturing metal parts by introducing an aluminium ingot into the graphite crucible to 750°C that exceeds the metal alloy's melting point. Boron carbide and red mud powders, preheated at 450°C for 30 minutes in a furnace or induction heater were added to the melt. Two percent magnesium was also mixed with molten aluminium to enhance wettability during mixing. To eliminate any contaminants, a degassing tablet containing solid hexachloroethane (C2Cl6) was introduced into the vortex, effectively removing impurities from the mixture. The slag that formed was subsequently removed from the molten metal. To ensure full mixing of the reinforced particle with the aluminium melt, a stirrer was utilized to generate a "Vortex. The stirrer was set to rotate at a speed of 300 rpm, to create a "vortex" for approximately five minutes. The mixture should be continuously stirred until a uniform consistency is achieved, and all impurities or inclusions have been eliminated. Pour the mixture into a mould and allow it to cool and solidify. Remove the casting from the mold and inspect it for any defects or imperfections. Test the composite for its desired properties.

2.2 Microstructural characterization

Following successful fabrication of the composite's, sectioned specimens were made ready by grinding using various grades of emery paper and polishing with velvet cloth and alumina powder. The microstructure of the composites was characterized using SEM. The prepared specimens were also subjected to EDX analysis.

2.3 Evaluation of Corrosion on the Prepared Specimens

The corrosion assessment was performed using a weight loss approach. The specimens for the corrosion studies were measured and machined to the requisite sizes. As-cast AL/B4C/RM hybrid composite samples with B4C weight percentages of 2%, 4%, 6%and 8%wt and constant 2% RM were developed. All the created samples were submerged in HCL solution (shown in Figure 1) for exposure duration that ranges from 24 to 96 hours in increments of 24 hrs, with normalities of 0.25, 0.5, 0.75 and 1.0 N. Submerged samples were removed after the predetermined amount of time, cleaned, and weighed to determine for reduction in weight (Figure 2(a-b)). The materials were also examined macroscopically using SEM.

The following formula can be applied to determine the corrosion rate:

$$\text{Corrosion Rate (CR) (mm/Year)} = \frac{K * \text{m loss}}{A * t * \rho}$$

where k is a constant 8.76 10^4 so that CR is in [mm/y], m loss is the mass loss [g] of the metal (m_0 - m_f) in time t [hours], A is the surface area [cm2], & ρ is the density [g/cm3]

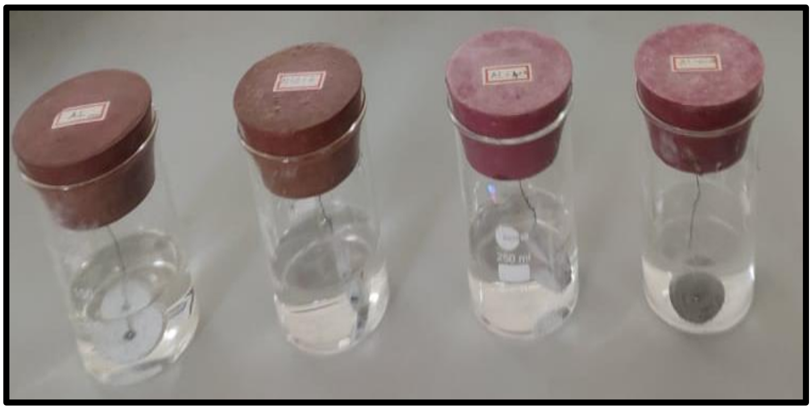


Figure 1: Immersion corrosion setup in HCl solution

Figure 2(a-b): a: Samples before immersion, b: Samples after immersion

2.4Taguchi Technique

The Taguchi method, a systematic approach widely used in industries like automotive, electronics, and aerospace, is employed in this study to optimize, the design and effectiveness of AL-B4C-RM hybrid aluminium MMC's. The Taguchi technique, founded on the principles of orthogonal array concept, aims to minimize experimentation cost and time while maximizing performance and quality[16]. By using a limited number of experimental sets, the technique identifies the best design parameters that control the process. The three chosen criteria, weight percentage of B4C, normality of solution, and immersion test time, each with four levels, are analysed by evaluating the means and variance of the chosen criteria. The Taguchi procedure is applied to establish the impact of these parameters on the corrosion behaviour of an as-cast composites, with the end goal of developing a mathematical equation that forecasts the rate of corrosion.

2.5 Experimental Design

The study utilized an orthogonal array for conducting experiments. Table 2 presents the control parameters, percent weight of B4C, normality of the solution, and exposure time with four corresponding levels. The study used L16 orthogonal array, as depicted in Table 3, which has 4 columns and 16 rows, indicating that it is analysing 3 parameters with 16 observations [22][23][24]. These parameters influence and establish the nature of corrosion in the composites.

Table 2: Control parameters & levels

Control Parameters	L- I	L- II	L-III	L- IV
R: % of Reinforcement	2	4	6	8
N: Normality	0.25	0.5	0.75	1.0
T: Immersion Time	24	48	72	96

Table 3:L16 Orthogonal array

Trial No.	%Reinforcement (R)	Normality (N)	Immersion Time in hours(T)	Corrosion Rate (mm/year)	S/N Ratio (db)
1.	2	0.25	24	4.33400	-12.7378
2.	2	0.5	48	5.14000	-14.2193
3.	2	0.75	72	5.74000	-15.1782
4.	2	1	96	4.72000	-13.4788
5.	4	0.25	48	4.14000	-12.3400
6.	4	0.5	24	5.18688	-14.2981
7.	4	0.75	96	4.05000	-12.1491
8.	4	1	72	5.01000	-13.9968
9.	6	0.25	72	2.80000	-8.9432
10.	6	0.5	96	3.27200	-10.2963
11.	6	0.75	24	5.03000	-14.0314
12.	6	1	48	5.33000	-14.5345
13.	8	0.25	96	2.25000	-7.0437
14.	8	0.5	72	3.44200	-10.7362
15.	8	0.75	48	3.98000	-11.9977
16.	8	1	24	5.25000	-14.4032

Experimental outcomes are then transformed into a S/N ratio and used to examine the Taguchi technique's quality attributes.

'The-lower-the-better' was employed for assessing corrosion rates for aluminium based hybrid composites since lower corrosion rates are desired in the study.

The S/N analysis was used to compute the S/N ratio for every level of the process components. Furthermore, a statistical analysis of variance (ANOVA) was utilized to discover the key variables. Consequently, the optimal combination of test parameters can be predicted, leading to the identification of the most favourable configuration for achieving the desired outcomes.

$$\frac{S}{N}\ Ratio = -10\log\frac{1}{n}\{y_1^2 + y_2^2 + \ldots\ldots + y_n^2\}$$

where $y_1, y_2, \ldots, y_n$ denote the responses for corrosion rate, with n representing the sum of records. The 'lower-the-better' characteristic is suitable for minimizing corrosion rate, and the corresponding S/N ratio conversion is employed. To determine the control parameters with statistical significance, a statistical technique of variance called ANOVA is conducted. The combination of ANOVA and the S/N ratio provides a valuable tool for predicting the optimal combination of corrosion factors with a reasonable level of accuracy.

Mean-response-diagrams were produced using the MINITAB software, and an ANOVA analysis was performed to assess the contribution % of the test parameters.

3 Results and Discussion

3.1 EDX and SEM analysis

EDX analysis, often referred to as energy-dispersive X-ray spectroscopy, is a technique applied to discover the elemental composition of the sample. It involves bombarding the sample with high-energy X-rays, which causes the atoms in the sample to emit characteristic X-rays. These emitted X-rays are then detected by an energy-dispersive detector and their energies are measured. The energies of the X-rays are specific to each element, by exploring the energy of the emitted X-rays, it becomes feasible to ascertain the elemental constituents of the sample. SEM of the as cast AL6061 and Boron carbide, red mud, hybrid -AL6061-B4C-RM composites are shown in Figure 3a-3g.

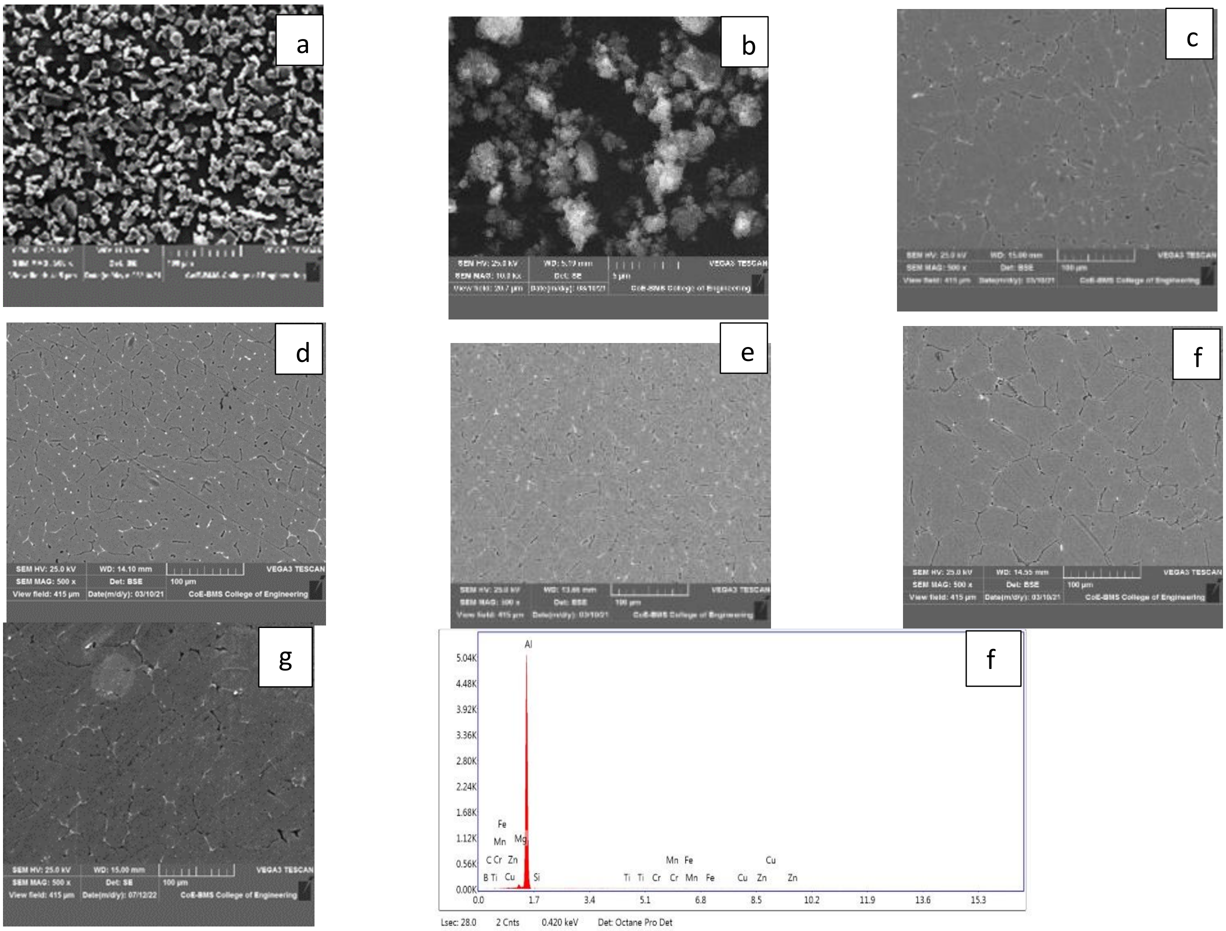


Figure 3 (a-g) :SEM Image of AL Composites (a-f): a) B4C b) red mud c) AL-6061 d) AL6061-2% B4C+2%RM e) AL6061-4%B4C+2%RM f) AL6061 -6% B4C+2%RM g) Al6061-8%B4C+2%RM f) EDX - Al6061-8%B4C+2%RM

3.2 Taguchi Method:

To mitigate the severity of the corrosion rate, the experiment's primary target was to pinpoint the critical parameters that have a significant impact on it. An orthogonal array was employed to carry out experiments and examine the influence of Reinforcement (R), Normality (N), and Immersion Time in hours (T) on the corrosion rate. The corrosion characteristics of the composites are determined by these aspects, which are known to affect the rate of corrosion.

Data collected through experimentation was converted into S/N ratio, determining how a certain factor affects the rate of corrosion. As per the S/N ratios presented in Table 4, the Normality of the solution, followed by the Immersion Time, and then percentage of Reinforcement, were the main factors impacting the corrosion rate. Hence, by analysing the response table provided in Table 4, it becomes feasible to identify the optimal parameter combination that curtails the overall corrosion rate. In conclusion, the combination of 8% reinforcement, 0.25 normality, and 96 hours of exposure (R4N1T4) lead to the lowest corrosion rate. ANOVA was employed to analyse the experimental results in greater detail, as the Taguchi technique does not offer an assessment of the impact of individual parameters.

Taguchi Analysis: CR versus R, N, T

Table 4: Response Chart for Signal to Noise Ratios, Lower is Better

Levels	% R	N	T
1	-13.90	-10.27	-13.87
2	-13.20	-12.39	-13.27
3	-11.95	-13.34	-12.21
4	-11.05	-14.10	-10.74
Delta	2.86	3.84	3.13
Rank	3	1	2

3.3 Influence of a Factor and ANOVA analysis

To achieve a more comprehensive interpretation of how individual parameters impact the performance, ANOVA was utilized in conjunction with the Taguchi technique. ANOVA was employed to investigate the influence of variables such as % reinforcement (R), normality (N), and time of immersion in hours (T), including their optimal level on the response variable, the corrosion rate. The ANOVA results showed the proportion of variance of each parameter on the corrosion rate and which levels of each factor had the greatest impact.

Table 5: ANOVA Analysis

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
%R	3	3.6178	23.91%	3.6178	1.2059	8.34	0.015
N	3	6.3948	42.26%	6.3948	2.1316	14.73	0.004
T	3	4.2513	28.09%	4.2513	1.4171	9.80	0.010
Error	6	0.8680	5.74%	0.8680	0.1447		
Total	15	15.1318	100.00%				

With a significance threshold of 0.05 and a 95% confidence level, the analysis was conducted. If a factor's P value was less than 0.05, it was considered to have a statistically significant impact upon the performance metric. The analysis also showed the proportion of each parameters contribution and its effect on the result. The conclusions of the ANOVA with regard of the rate of corrosion in this analysis are disclosed in Table 5.

The findings from Table 5 reveal that the parameter with the maximum affect on the corrosion rate is Normality, with a proportion of variance of 42.26%. The second most influential factor is time of immersion, with a proportion of variance of 28.09%The least influential parameter is the % of reinforcement, which accounts for only 23.91% of the variance in the corrosion rate.

3.4 Influence of Testing Parameters on Corrosion Rate

The principal impacts on the corrosion rate of various testing parameters, as displayed in Figures 3a and 3b, can be visualized by the plots of means and S/N ratios. The steepness of the line for each parameter indicates its impact on the corrosion rate. A factor with a relatively flat line has minimal influence, whereas a factor with a steep line has a significant impact. From the plots, Normality has the extremely significant impact on the corrosion rate, while the other factors have a less significant impact [20][21].

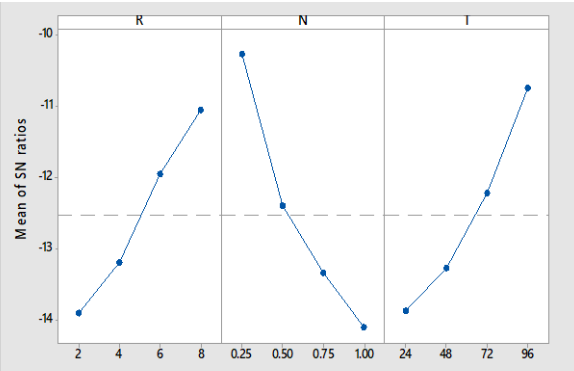


Figure 3a: Main effect plot-S/N ratios

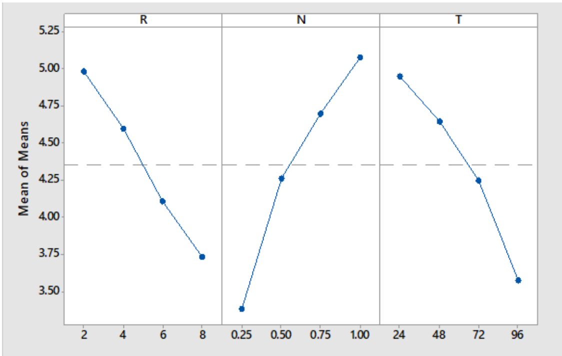


Figure3b: Main effect plot-Means

3.5 Multiple Linear Regression Models

Multiple linear regression analysis was used to model the corrosion rates of composite materials, conducted in MINITAB statistical software program. The subsequent model that is produced establishes a direct association between the unidentified variable and the identified variables. The contemporary study divulges a apparent relationship between the corrosion rate and the Reinforcement (R), Normality (N), and the immersion time in hours (T). The ANOVA analysis was employed to generate a linear regression equation utilizing the given values of Reinforcement, Normality, and the immersion time in hours.

The corrosion rate's linear regression equation, established through the analysis of variance is as given below:

Corrosion Rate (mm/year) =5.167- 0.2124 R (wt. % B4C) + 2.212 N (normality) - 0.01888 T (Immersion time)

The equation (2) provides a statistically significant model for forecasting the corrosion rate based on the Reinforcement (R), normality (N), and immersion time in hours (T). By substituting the experimentally obtained values for these variables, the corrosion rate of the hybrid - composite can be calculated with reasonable accuracy.

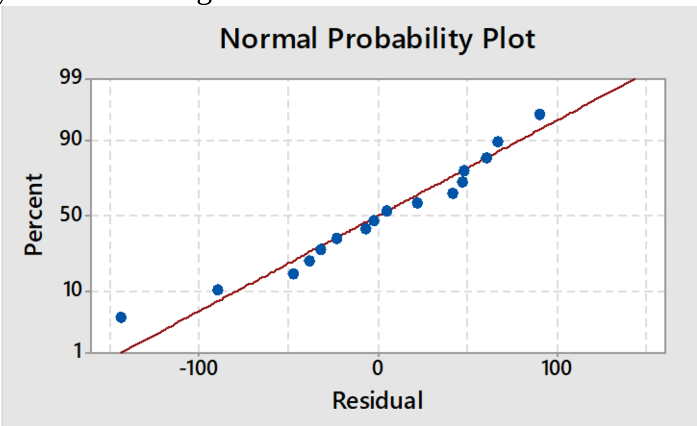


Figure 4: Residuals' normal probability graphs for the rate of corrosion of Al hybrid composites

The residuals' normal probability plot was analysed, as shown in Figure 4, to confirm the model provided by Equation (2) was effective. The close alignment of the plot's data points with the normal probability line is a clear indication that the model is acceptable. Hence, the equation (Eq. 2) generated to determine the corrosion rate of the aluminium composite is deemed acceptable.

3.6 Confirmation Test

After determining the optimal settings, the next step involves predicting and verifying the improvement in performance of the responses. The conclusions of the study were validated by confirmation tests. The outcomes of the confirmation experiment are further inferred from Table 6 to be in good accord with the expected values.

Table 6:Findings from the validation experiment.

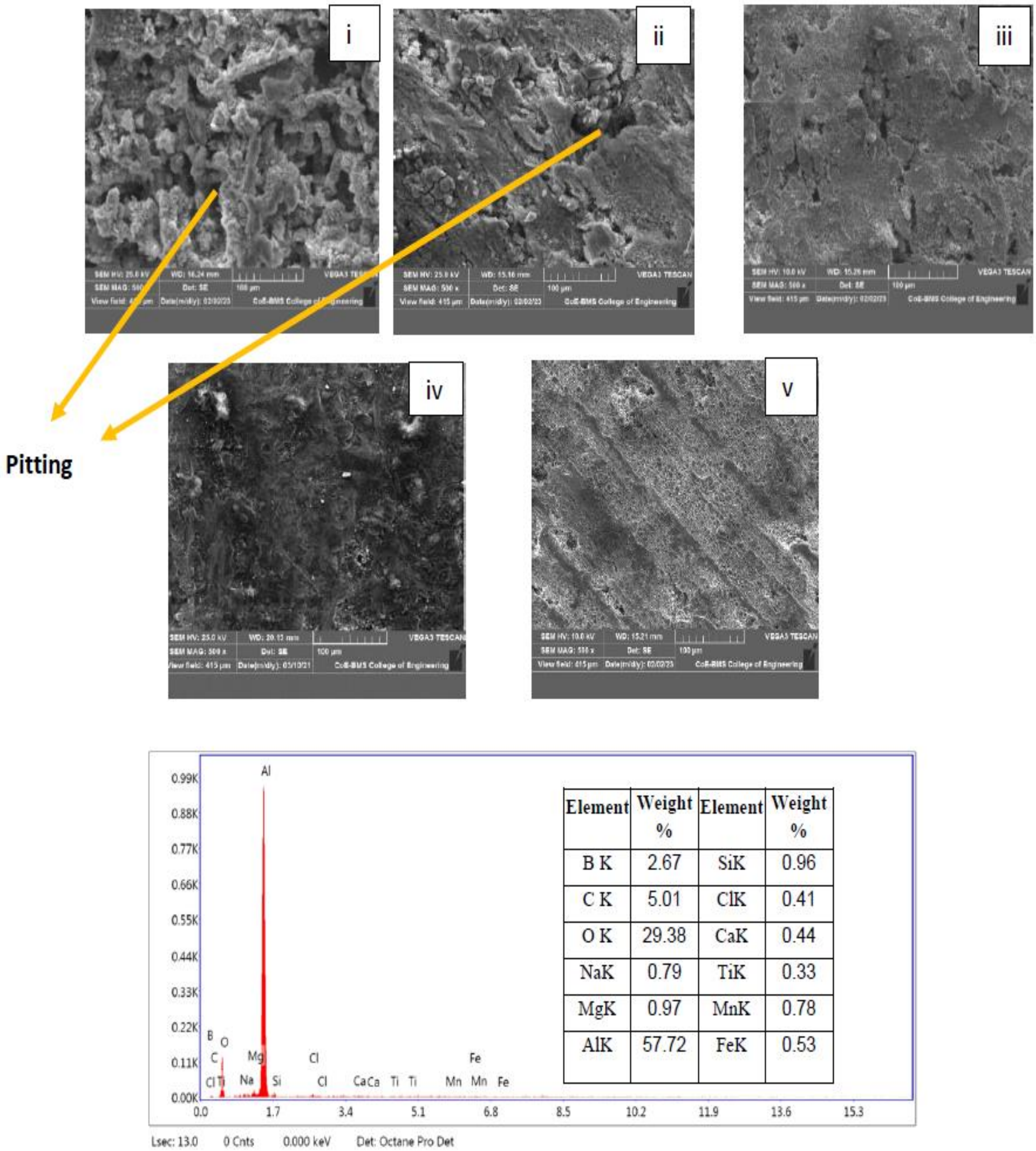
Optimal Design Parameters		
Predicted value	Experimental value	Error%
R4N1T4	R4N1T4	
-7.00527	-7.04365	0.547

3.7 Corrosion Analysis

From the SEM photomicrograph in Figure 4, it can be observed that the AL-6061 specimens without reinforcements and hybrid composites encompassing 2 - 8 wt.% B4C reinforcement underwent surface corrosion after being exposed to a HCL corrosion medium with a normality of 1 N for 96 hours. However, a notable trend is that the degree of surface degradation appears to decrease with increasing B4Ccontent. The SEM analysis revealed that severe pitting occurred on the surface of the unreinforced monolithic aluminium specimen, while the composites containing B4C exhibited significantly less pitting.

SEM micrographs can be used to observe the surface of a material before and after corrosion, along with to compare the level of surface degradation caused by corrosion with different B4C content levels [25]. After a 96-hour test period in 1 N HCl,

Figure 4 displays SEM of corroded surfaces of composites reinforced with 2 and 8 weight percent B4C and 2% RM. The images imply that the extent of surface degradation decreases as B4C content increases. 2% hybrid composite specimens exhibit severe pitting compared to 8% hybrid composites. The enhanced corrosion resistance of the composites can be credited to the reinforcing particles, which alter the microstructure of the matrix and act as a protective shield against the onset and expansion of pitting corrosion. The reinforcement particles alter the matrix's grain structure continuity, hindering the penetration of corrosive agents, and act as a physical shield by blocking the access of corrosive agents to the matrix, preventing the formation of surface pits. EDX analysis of Al- hybrid composites indicates the presence of boron carbide and red mud particles in alloy of AL-6061 matrix.



Element	Weight %	Element	Weight %
B K	2.67	SiK	0.96
C K	5.01	ClK	0.41
O K	29.38	CaK	0.44
NaK	0.79	TiK	0.33
MgK	0.97	MnK	0.78
AlK	57.72	FeK	0.53

Figure 5: corrosion on the AL-6061 and HMMCS alloy i) as-cast, ii) 2 wt. % B4C, iii) 4 wt. % B4C, iv) 6 wt. % B4C v) 8 wt. % B4C vi) EDAX of AL- hybrid composites

4 Conclusions

The immersion corrosion test was carried out on AL6061 metal matrix composites that were manufactured using different amounts of B4C particles (2.0% - 8%) and constant 2% red- mud, led to certain conclusions**.**

- The stir casting liquid metallurgical approach was employed to effectively produce AL/B4C/RM-based MMCs with reinforcement of B4C in weight percentages ranging from 0 to 8% and constant 2% red mud.
- The results showed that while the initial weight loss was substantial, there was a noticeable decrease in weight loss and the corrosion rate as the time progressed.
- As the weight % of the reinforcement increased, the corrosion through weight loss of the composite reduced.
- The results from the current study indicate that the calculated corrosion rate, using a linear regression equation specifically established for this study, aligns well with the investigational information.
- The outcomes of the immersion corrosion assessments indicate that the minimum corrosion rate was accomplished when the composite material was immersed in a HCl solution with a normality of 0.25 N, with 8% B4C reinforcement, and for a duration of 96 hours. The S/N ratio analysis determined that the normality had the utmost influence on the corrosion rate, then immersion time and of % of reinforcements. The ANOVA results showed that the normality had the highest effect on the rate of corrosion, with 42.26%. subsequently the immersion time 28.09% and weight percentage of reinforcements with 23.91%.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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