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Examining Aluminium Metal Matrix Composite Reinforced with Aluminium Oxide for Automotive Application's Corrosion Resistance

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Abstract:- Recent years have seen a substantial increase in interest in metal matrix composites (MMCs) because of their exceptional corrosion resistance and superior mechanical qualities. Due to their lightweight, high strength, and corrosion resistant qualities, aluminum and its alloys are used extensively across a variety of industries, but particularly in the manufacturing and aerospace sectors. Aluminum can be mixed with other substances, such as aluminum oxide (Al2O3), to create MMCs, further enhancing these qualities. In the proposed study, two MMCs were created by mixing aluminum with weight-proportionate amounts of 7% and 8% Al2O3. Using a salt spray corrosion test that lasted 96 hours, the corrosion resistance of these MMCs was assessed. The results of the corrosion tests revealed that both MMCs have a much higher corrosion resistance than pure aluminum. The Al2O3 particles in the MMCs, which serve as barriers against the migration of corrosive species to the metal matrix, can be credited for this. The outcome demonstrates that otter factors have a major impact on composite material corrosion behavior as well.

Keywords: *Equal channel angular pressing (ECAP), Aluminum oxide (Al2O3) Metal Matrix Composites (MMCs), ceramic matrix composites (CMCs), Aluminum-Based Metal Matrix Composites (AMMCs), ANOVA, Taguchi – Grey Relational Analysis.*

1. Introduction

Composites

Metal Matrix Composites (MMCs) represent a class of materials distinguished by their incorporation of various reinforcing elements, such as continuous fibers or particle whiskers, dispersed within a metal matrix. These composites are fabricated through intricate processes including powder blending, consolidation, and physical deposition. Aluminum-based Metal Matrix Composites (AMMCs) have surged in demand due to their exceptional properties—increased specific strength, reduced density, commendable wear resistance, corrosion resilience, and superior thermal characteristics. Stir casting stands as the predominant method for crafting these AMMCs.

A pivotal focus within the realm of AMMCs revolves around their wear behavior, specifically the exploration of their wear attributes when fortified with 7% and 8% aluminum oxide (Al2O3). The drum testing method serves as a means to unravel the nuanced wear patterns exhibited by these composites. In parallel, studies have delved into the corrosion behavior and resistance of aluminum and its alloys. Researchers have investigated various facets such as the ultrahydrophobic laser-patterned aluminum surfaces and their corrosion resistance in saline solutions. Furthermore, examinations into the corrosive mechanisms in alloys comprising aluminum, zinc, and zinc-sn in sodium chloride solutions have been conducted, unraveling the effects of alloying elements and their impacts on corrosion rates. Complex analyses have dissected the corrosion behavior of aluminum and its alloys under diverse conditions, spanning aqueous, acidic, alkaline, saline solutions, as well as environments containing noxious gasses and industrial pollutants. These studies offer comprehensive insights for materials scientists and engineers navigating the intricacies of corrosion phenomena in aluminum-based materials.

Studies have also ventured into innovative processing techniques, such as plastic flow machining, ultrasonic rolling, and equal channel angular pressing (ECAP), to modify the structure and properties of aluminum alloys. These methodologies aim to enhance mechanical characteristics, corrosion resistance, and fatigue properties by manipulating grain structures, dispersing particles, and inducing gradient structures within aluminum-based materials. Explorations into local cladding types as a means of mitigating corrosion damage on aircraft aluminum structures have showcased promising results, indicating the potential to arrest corrosion-induced degradation in tensile and fatigue properties. Macroscopic stress concentration factors have been pivotal in evaluating corrosion damage by accounting for the diminished mechanical properties resulting from corrosive effects. Natural fiber composite materials can also be fabricated and tested for their various mechanical and thermal behaviors [21-26].

2. Materials and Methods

2.1 Aluminum 6061

Aluminum 6061, an alloy distinguished by its multifaceted properties of excellence, commands substantial significance within the domains of aerospace and automobile engineering. Its ubiquity in various pivotal applications arises from the alloy's juxtaposition of lightweight characteristics and structural robustness. Within the aerospace realm, Aluminium 6061 serves as a pivotal constituent in the assembly of aircraft structures, predominantly attributable to its remarkable strength-to-weight ratio. Its innate lightweight constitution invariably contributes to the curtailment of fuel consumption, thereby elevating the overall operational efficiency of aircraft. Furthermore, the alloy's inherent resistance to corrosion endows it with an extended operational lifespan, particularly indispensable given the taxing environmental rigors inherent to aerospace operations. Components spanning aircraft frames, fuselage panels, and interior fittings all derive pronounced benefits from the alloy's enduring properties and ease of fabrication. Similarly, within the automotive sector, Aluminium 6061 assumes a paramount role in the pursuit of augmented fuel efficiency and enhanced vehicular performance. By supplanting more weighty materials like steel, the alloy effectively mitigates the overall vehicular mass, thereby instigating advancements in fuel economy and concomitant reductions in emissions. The alloy's remarkable machinability further facilitates the realization of intricate automotive designs, ushering in a new era of innovative structural configurations that judiciously balance safety and efficiency considerations. Moreover, Aluminium 6061's innate thermal conductivity attributes render it invaluable in the manufacturing of engine components and heat exchangers. This, in turn, engenders an efficacious dissipation of heat, thus augmenting engine performance. Its innate resistance to corrosion, a distinctive hallmark, certifies the enduring durability of automobile components, even when subjected to the gamut of environmental exigencies. In summation, Aluminum 6061 stands as an indispensable material within the aerospace and automobile sectors, furnishing pivotal support to the relentless pursuit of lightweight, enduring, and fuel-efficient engineering designs, thus indelibly shaping the trajectory of future transportation technologies[1].

2.2 Al2o3 Matrix Composites

Aluminum oxide (Al_2O_3) Metal Matrix Composites (MMCs) represent the zenith of sophisticated material engineering, merging the inherent robustness of aluminum with the reinforcing capabilities of aluminum oxide. This composite entails an intricate matrix, integrating an aluminum alloy infused with finely dispersed aluminum oxide particles. The production methodology for Al_2O_3 MMCs typically involves intricate techniques such as powder blending, consolidation, and physical deposition.

The integration of aluminum oxide within the aluminum matrix confers a myriad of advantageous attributes onto the composite. These encompass heightened tensile strength, augmented rigidity, superior wear resistance, and commendable thermal conductive properties. Furthermore, the incorporation of aluminum oxide facilitates a reduction in the composite's density, yielding an optimal amalgam of strength and reduced mass—an indispensable facet in the realms of engineering and structural design. Al_2O_3 MMCs find widespread applicability across industries requiring materials endowed with exceptional mechanical properties coupled with robust defenses against wear and corrosion. Their application spans diverse domains, encompassing aerospace engineering, automotive components, structural frameworks, and even electronic packaging owing to their remarkable thermal conductivity.

The enhancement of wear characteristics in Al2O3 MMCs, scrutinized through methodologies such as drum testing, has garnered considerable interest. Researchers strive to intricately adjust the composition and processing parameters to finely modulate the dispersion and synergy of aluminum oxide particles within the aluminum matrix, thereby augmenting the material's wear resistance, mechanical robustness, and thermal resilience. Persistent advancements in fabrication methodologies and a nuanced understanding of the intricate interplay between the aluminum matrix and aluminum oxide reinforcements persist in charting the trajectory for the evolution and extensive utilization of Al2O3 MMCs in the forefront of cutting-edge technological and industrial domains.

2.3 Stir casting Process

The vertical stir casting process assumes paramount significance in the fabrication of cutting-edge composite materials. It encompasses the liquefaction of a matrix material, often composed of a metallic substrate or alloy, within a vertically oriented crucible. This occurs concomitantly with the deliberate introduction of reinforcing particles or fibers, facilitated by a meticulously controlled stirring apparatus. This meticulous procedure ensures the methodical dispersion of reinforcements, ultimately yielding composites endowed with enhanced properties. Its irreplaceable role resonates prominently within sectors such as aerospace, automotive, and defense, where it holds particular import in the production of both metal matrix composites (MMCs) and ceramic matrix composites (CMCs). In essence, it stands as a precision-driven and versatile technique for the formulation of superlative materials spanning a diverse spectrum of industries.

2.4 ASTM Standard

In the realm of materials engineering, the esteemed ASTM B117-19 standard is rigorously adhered to, embodying a paramount significance when applied to Aluminum-Based Metal Matrix Composites (AMMCs). This standard represents an encompassing framework, meticulously designed, for the comprehensive assessment of corrosion resistance, endurance, and reliability, all of which assume pivotal roles in the meticulous evaluation of AMMCs' performance and their aptitude for multifarious industrial applications.

Within the contours of ASTM B117-19, a meticulously controlled and scientifically rigorous regimen is prescribed for the accelerated corrosion testing of AMMC specimens. Employing the sophisticated apparatus of a specialized environmental chamber, this standard adeptly recreates severe environmental conditions, encompassing exposure to saline mists and corrosive agents, thereby effectively expediting the manifestation of corrosion phenomena that would conventionally necessitate an extended period to materialize in real-world operational settings. This venerable standard's ambit encompasses an intricate array of parameters, encompassing but not limited to corrosion rate, the visually observable progression of corrosion, and the sustained structural integrity of AMMC specimens.

These painstaking examinations are diligently conducted with an astute focus on illuminating the material's inherent vulnerability to corrosive degradation, in addition to meticulously cataloging the extent and nuanced characteristics of these corrosive effects. Characterized by its intricate design and the exacting enforcement of its protocols, ASTM B117-19 emerges as an indispensable tool wielded by a cohort of researchers, engineers, and industry practitioners deeply engrossed in the realms of AMMC development and implementation. Its intricate methodologies, coupled with stringent evaluation criteria, empower this community to discern, with unparalleled precision, the durability, resilience, and holistic performance of AMMCs when subjected to the crucible of corrosive challenges, thereby facilitating a nuanced comprehension that informs judicious decision-making and propels the frontiers of materials science toward the realization of avant-garde materials endowed with superlative corrosion-resistant attributes.

2.5 Salt spray test

The assessment of materials and surface coatings' resistance to corrosion is conducted through the salt spray test, also recognized as the salt fog test, a prevailing and standardized method in corrosion analysis. Typically applied to metallic substrates with protective surface coatings, this evaluation method expedites the corrosion process, scrutinizing the capacity of coatings to shield the underlying metal from deteriorative effects. While predominantly used for metallic surfaces, this method extends its scope to encompass stone, ceramics, and polymers for evaluation purposes. The exposure of coated samples to a corrosive environment accelerates corrosion, serving as a means to gauge the suitability of a protective finish. Observation of corrosion-related manifestations such as rust or various oxides follows a designated period, with the time taken for corrosion emergence serving as a comparative metric. The duration of the test varies depending on the degree of corrosion resistance offered by the coating, irrespective of its robustness. Esteemed as one of the most favored corrosion assessments, the salt spray test finds its origins in the initial establishment of the ASTM B117 standard in 1939, with additional crucial benchmarks including JIS Z 2371, ASTM G85, and ISO 9227.

3. Result and Discussion

Table 1: Process control parameters and levels

S. No.	PARAMETER	LEVEL 1	LEVEL 2	LEVEL 3
1	% Reinforcement	0	3	6
2	pH Value	3	6	9
3	Time (Hr)	48	72	96

Table 2: Output Responses for L9OA

Trial	% Reinforcement	pH Value	Time (Hr)	Corrosion Rate (g/Hr)
1	0	3	48	0.000277
2	0	6	72	0.000199
3	0	9	96	0.000151
4	3	6	96	0.000128
5	3	9	48	0.000229
6	3	3	72	0. It 000149
7	6	9	72	0.000121
8	6	3	96	0.000090
9	6	6	48	0.000190

3.1 Optimisation of Taguchi's Single Process Characteristics Using the Signal to Noise (S/N) Ratio

Within Table 3, Time emerges as the variable exhibiting the most substantial "max-min" value, standing notably at 5.6107. Ergo, this parameter wields a considerable influence on the corrosion rate. Following closely in significance is the reinforcement factor, boasting the second-highest "max-min" value of 4.05. Considering the findings elucidated in Table 3, the optimal benchmarks for achieving an ideal Corrosion Rate align with a Reinforcement percentage of 6%, a pH Value of 9, and a Time span of 96 hours. The results of the mean S/N Ratio indicate that time is the most significant variable, followed by reinforcement %. We employ grey relational analysis with a Taguchi foundation to confirm the aforementioned prediction [4,7].

Table 3: Analysis of S/N Ratio

Response Parameter	Input Parameter	Mean GRG Level 1	Mean GRG Level 2	Mean GRG Level 3	Max - Min
Corrosion Rate	% Reinforcement	73.8686	75.7344	**77.9186**	4.0500
Corrosion Rate	pH Value	76.2207	75.4437	**76.7235**	1.2797
Corrosion Rate	Time (Hr)	72.7963	76.3184	**78.4069**	**5.6107**
Corrosion Rate	Total mean to GRG = 75.9368				Optimum level = R3 P3 T3

The examination of the mean S/N Ratio's results reveals that time, followed by reinforcement percentage, is the most important variable. To verify the aforementioned prediction, we use grey relational analysis with a Taguchi foundation.

Table 4: ANOVA for SN Ratio

S.NO	Factor	DF	Adj SS	Adj MS	F-Value	P-Value	Effective Factor (%)
1	% Reinforcement	2	24.6541	12.3271	658.05	0.002	33.39
2	pH Value	2	0.9068	0.4534	24.20	0.040	1.22
3	Time (Hr)	2	48.2474	24.1237	1287.78	0.001	65.34
4	Error	2	0.0375	0.0187			0.05
5	Total	8	73.8458	-	-	-	100

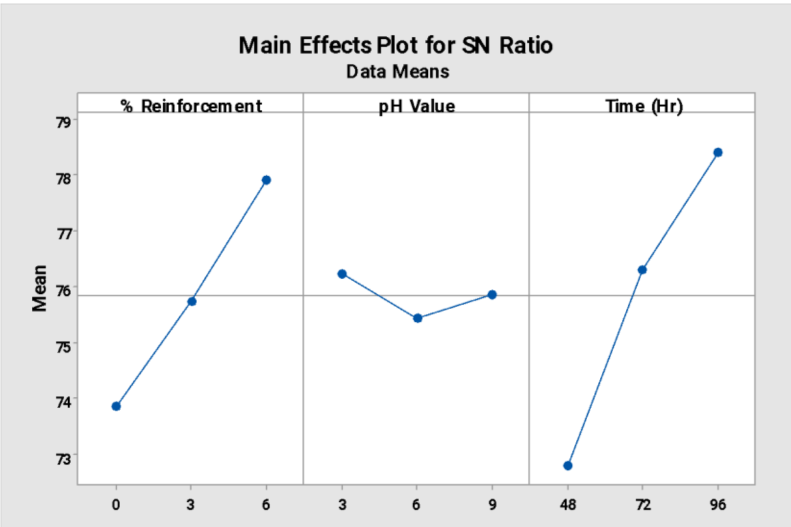

Figure. 1 Main effects plot for SN Ratio

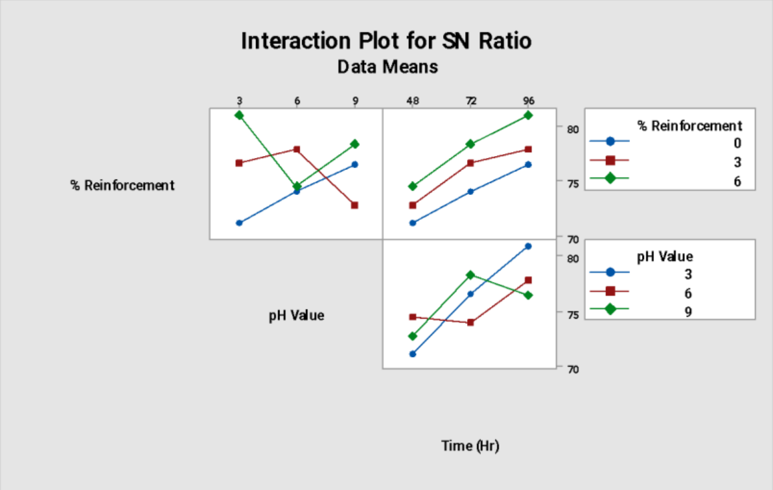

Figure. 2 Interaction plot for SN Ratio

3.2. Taguchi – Grey Relational Analysis

One of the best methods for dealing with imprecision, numerous process characteristic criteria, and unique data is the grey theory [18–20]. The steps in the procedure are as follows: Equation (1) was used to normalize the surface roughness (Ra) and kerf angle (Ka) S/N ratio values (lower is better).

Xi ^* (j) = max(Xi(j))-Xi(j) / (Xi(j))-(Xi(j)) (1)

1. The Grey Relational Coefficient (ξi(j)) is calculated using equation (2)

(ξi(j)) = min ^ + min / 0*i* ^(j)+ max (2)

where, Δ_{0i}(j) is the deviation sequence of the reference sequence,

oi^(j) = ||Xo ^* (j) - Xi ^* (j)||

max = max/j ||Xo^*(j) - Xi^* (j)

min = min/j ||Xo^* (j) - Xi^* (j)||

ζ is identification or distinguishing coefficient in the range (0 to 1), generally ζ = 0.5 is used

2. The grey relational grade (GRG) is calculated using equation(3)

oi = 1/n Σj=1 ^n i ^ (j) (3)

Since each factor's impact on the system differs slightly in practice, equation (3) is changed to read as follows.

oi = Σj=1 ^ n Wji (j) (4)

Where Wj represents the weighted average value of i and Σj=1 ^ n Wji = 1

GRG is shown in Table 4, which confirms that the machinability parameter points of trial 8 have the highest GRG.

Table 5: Normalised Data and Grey Relational Grade

Trial	Normalised Data	Grey Relational Coefficients (GRC)	Rank
1	1.0000	0.3333	9
2	0.7051	0.4149	7
3	0.4626	0.5194	5
4	0.3169	0.6121	3
5	0.8318	0.3754	8

Trial	Normalised Data	Grey Relational Coefficients (GRC)	Rank
6	0.4483	0.5273	4
7	0.2650	0.6536	2
8	0.0000	1.0000	1
9	0.6639	0.4296	6

Table 6: Analysis of GRG

Response Parameter	Input Parameter	Mean GRG Level 1	Mean GRG Level 2	Mean GRG Level 3	Max - Min
Corrosion Rate	% Reinforcement	0.4225	0.5049	**0.6944**	0.2718
Corrosion Rate	pH Value	0.6202	0.4855	**0.6316**	0.1461
Corrosion Rate	Time (Hr)	0.3794	0.5319	**0.7105**	**0.3310**
Corrosion Rate	Total mean to GRG = 0.5534				Optimum level = R3 P3 T3

Results of analysis of mean GRG shows that Time is the most significant variable followed by % Reinforcement. We go for Taguchi based grey relational analysis to confirm the above prediction.

Table 7: ANOVA for GRG

S.NO	Factor	DF	Adj SS	Adj MS	F-Value	P-Value	Effective Factor (%)
1	% Reinforcement	2	0.11658	0.058291	6.98	0.125	35.55
2	pH Value	2	0.02991	0.014954	1.79	0.358	9.12
3	Time (Hr)	2	0.16473	0.082363	9.86	0.092	50.23
4	Error	2	0.01670	0.008350			5.1
5	Total	8	0.32792	-	-	-	100

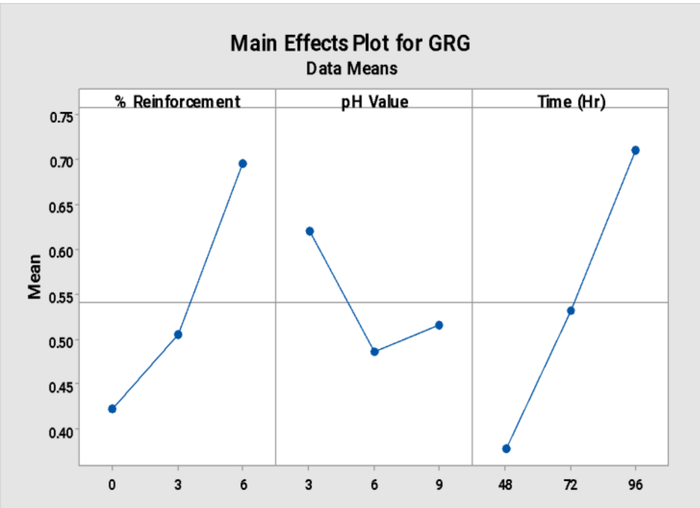

Figure. 3 Main effects plot for GRG

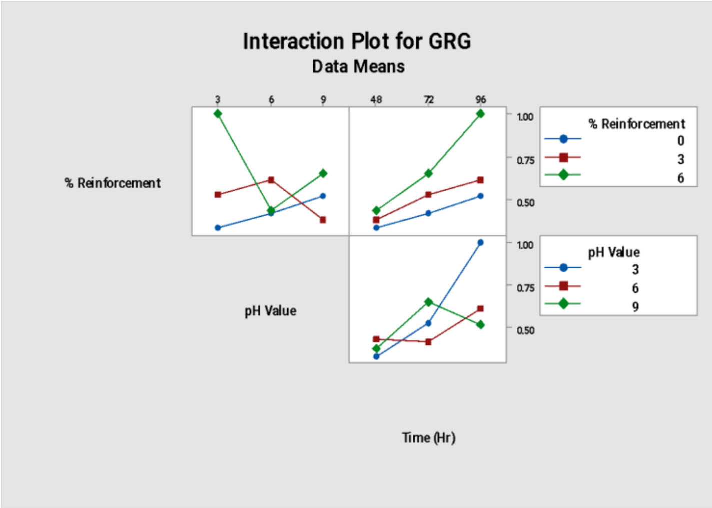

Figure. 4 Interaction plot for GRG

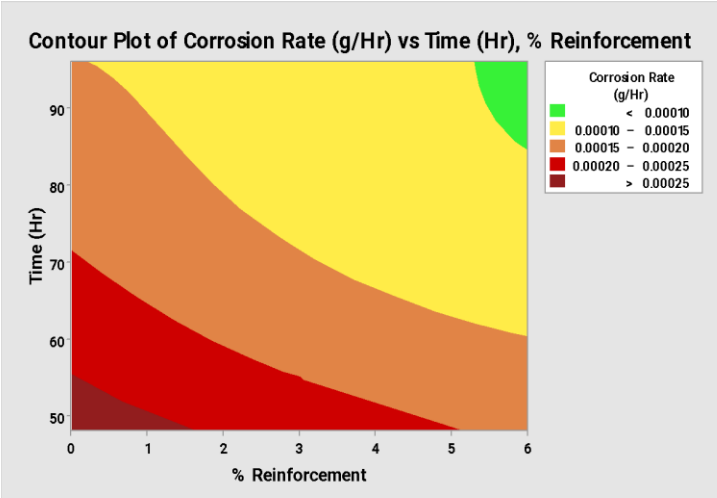

Figure. 5 Contour plot for Corrosion Rate VS Time

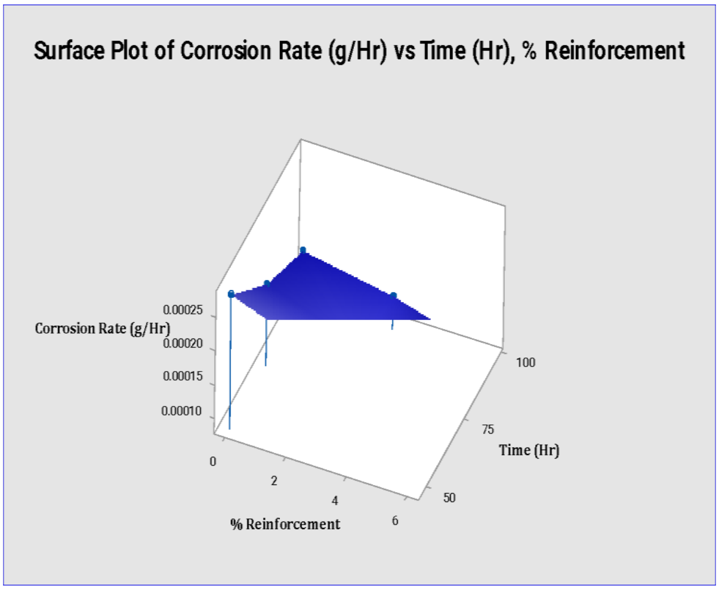

Figure. 6 Surface plot of Corrosion Rate VS Time, % Reinforcement

Confirmation Test

% Reinforcement	pH Value	Time (Hr)	Change in weight (g)	Corrosion Rate (g/Hr)
7	9	96	0.0083	0.000086

For 7% Reinforcement average value for 3 samples with 3 test each

% Reinforcement	pH Value	Time (Hr)	Change in weight (g)	Corrosion Rate (g/Hr)
8	9	96	0.0129	0.000134

4. Conclusion

The production of two Metal Matrix Composites (MMCs) by amalgamating aluminum with 7% and 8% Al2O3, guided by recommended research protocols, was successfully achieved. The assessment of these MMCs' resistance against corrosion involved a rigorous 96-hour salt spray corrosion examination. Both iterations of MMCs showcased markedly higher resistance to corrosion compared to pure aluminum, a testament to the role played by Al2O3 particles within the MMCs, acting as effective barriers that impede the migration of corrosive elements to the metal matrix. The study's findings underscore the significant influence of various factors, including the nature and quantity of reinforcing agents employed, as well as manufacturing conditions, on the corrosion response of MMCs.

This study unequivocally accentuates the inherent advantages of integrating MMCs across diverse industrial domains. Their exceptional mechanical attributes and robust corrosion resilience position MMCs as prime candidates for deployment in settings characterized by corrosive and hazardous environments. Al2O3 emerges as one of the reinforcing constituents capable of augmenting MMC capabilities, rendering them more apt for high-performance applications. The study's revelations pertaining to the interrelation between distinct characteristics and the corrosion proclivity of MMCs hold promise in refining MMC processing methodologies and design paradigms. The burgeoning potential applications and future trajectories for these MMCs underscore the importance of continued research into their characteristics and behaviors in varying environmental contexts, leveraging the insights gleaned from this study. Anticipated surges in the utilization of these MMCs across aerospace, automotive, and marine engineering sectors are on the horizon, buoyed by their exceptional mechanical prowess and corrosion-resistant attributes. Leveraging the research outcomes, there lies a prospect of fashioning novel MMC variants tailored for specific applications, leveraging enhanced functionalities. Overall, this study offers invaluable insights into the vast potential and versatile applications of MMCs across a wide expanse of industrial sectors.

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