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Corrosion Behaviour of Al2024 Metal Matrix Composites Reinforced with Al_2O_3

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Abstract: In this study, Al2024 metal matrix composites reinforced with Al_2O_3 of 0.063 - 0.200 mm particle size varying from 0 to 6 weight percentage were fabricated by vortex method. The effect of the Al_2O_3 particle on Al2024's corrosion behaviour has been investigated. The distribution of particles in all metal matrix composites appears to be quite homogenous, according to the SEM study of the microstructures. Weight loss corrosion studies have been performed on both MMC and corresponding base alloys using 0.05N and 0.1N HCl as corrosive media. The composites have a less susceptibility to pitting and corrosion than the matrix alloy, potentially because of the passive Al_2O_3 layer found in the MMCs. Using the potentiodynamic polarization test, the effect of reinforcement on the corrosion characteristics of composites in 0.05N and 0.1N HCl media was examined. The weight loss method was used to conduct stress corrosion tests for varying acidic medium temperatures (30°C – 55°C), normalcy (0.025 N-0.1 N), and exposure times (10-60 min). The rate of corrosion of Al2024 alloy was found higher than the Al_2O_3 reinforced Al2024 alloy.

Keywords: Al2024, Al_2O_3, Metal Matrix Composites, Weight Loss Corrosion, Potentiodynamic Polarization, Stress Corrosion, Resource Efficiency

1. Introduction

Metal matrix composites (MMCs) are composite materials whereby metals serve as the basis or matrix, and reinforcing elements, either organic or ceramic are added to the composite to enhance its properties relative to the base metal. Due to their appropriate qualities and affordable availability, aluminium matrix composites (AMCs), copper matrix composites and magnesium matrix composites are a few examples of MMCs that are in demand these days in a different types of applications such as the automotive, aerospace, and electronics industries, among others [1, 2]. These days, the most widely utilized MMCs are aluminium matrix composites (AMCs) and hybrid aluminium matrix composites (HAMCs) [3]. Aluminium matrix composites are a class of composites where non-metals are used as reinforcements and aluminium or aluminium alloy serves as the basis material (matrix). Reinforcements can be added in many forms, such as fibers, whiskers, and particles, and in different percentages of weight or volume. Multiple reinforcing materials are added to the aluminium matrix in a hybrid aluminium matrix (HAMC). When compared to conventional metals and alloys, particles-reinforced aluminium matrix composites have a very high strength to superior wear resistance, high stiffness, weight ratio, controlled coefficient of thermal expansion, higher fatigue resistance, and better stability at elevated temperatures. They have high electrical and thermal conductivity, making them appropriate for designing a variety of components for sophisticated applications [4-7].

The processing method has a significant impact on the composite's properties. Stir casting method is cost-effective that is favoured for large-scale manufacturing, making it an appropriate processing technique for creating hybrid and aluminium matrix composites. Stirring duration, speed, impeller location, impeller size, and impeller blade angle are the primary variables affecting the distribution of the reinforcements in the matrix.

The reinforcing material needs to be widely available and reasonably priced for the composite to be employed in commerce. The behavior of the alumina Al_2O_3 particles that are reinforced in the MMC mostly determines the general properties of these composites [8]. Al_2O_3 particle-reinforced aluminum composites, or Al-Al_2O_3, are regarded as among the most effective and efficient MMCs produced to date because of their improved mechanical properties when compared to other metal oxide reinforcements like TiO_2, SiO_2, ZrO_2 [9-12].

There are various approaches to assess the rate at which corrosion occurs. One popular technique is the weight loss method [13, 14]. Corrosion can occur at a slow or fast speed. Using this method, a sample of a certain material is exposed to a process environment for a set period of time. After that, the specimen is taken out for examination, where the first step is to assess the amount of weight lost during the exposure period. The corrosion rate is then used to express this weight loss [15].

One of the DC electrochemical methods for corrosion determination that is most frequently employed is potentiodynamic polarization measurement (PDP). The Tafel slope of the polarization curve can be utilized to determine the metal's corrosion potential and rate under the specified conditions.

Particle reinforced aluminium is used in many different thermal environments, particularly in automotive engine parts that must have better mechanical qualities and be resistant to chemical attack in acidic and air environments. Examples of these parts include brake drums, brake rotors, cylinders, and pistons. A thorough understanding of the corrosion behaviour of Al composites is crucial for applications involving high temperatures. Various investigations have shown that the quantity of pitting in Al2024 increased with volume fraction [16–18]. This could result from preferential acidic attack at the interface between the matrix and reinforcement [19].

The corrosion behaviour of Al2024 is complicated despite these factors tthat depends on the matrix alloy, alloying components, and kind of reinforcement [20]. This study aims to comprehend the impact of reinforcement on the corrosion behaviour, stress corrosion behaviour, and weight loss of Al2024 under various normalities of hydrochloric acid solution. Stress corrosion is a great test for high pressure and temperature in an autoclave.

2. Experimental procedure

2.1 Materials

In this study, Al2024 (Fenfee Metallurgical Pvt. Ltd, Harohalli, Kanakapura main road, Bangalore), Al_2O_3 (0.063 - 0.200 mm particle size, Fenfee Metallurgical Pvt. Ltd Bangalore, Karnataka, India), Hydrochloric acid (HCl, Merck), Hexachloroethane (C_2Cl_6) are used. The chemical composition of Al_2O_3 particles are tabulated in Table 1.

2.2 Preparation of Al2024/Al_2O_3 composites

The alloy was prepared by the vortex process in liquid metallurgy. An alumina-coated mechanical impeller was plunged into the liquid-temperature metal matrix alloy (800ºC), creating a vortex. In order to stop ferrousions from migrating from the impeller into the melt, the impeller must be coated. Particles of Al_2O_3 that had been heated were added to the melt. The addition of Al_2O_3 particles to the vortex was done with care to guarantee a continuous and smooth flow. For a uniform dispersion in the melt, the molten metal was swirled at 400 rpm while covered with an argon gas cover.

Table 1. Chemical composition of Al_2O_3 particles

Elements	α-Alumina	Fe_2O_3	TiO_2	CaO	Other Materials
Composition wt. %	96.2	0.7	1.7	1.2	0.2

Figure 1 (a) External view of electrical resistance furnace, **(b)** Metallic dies with 18 mm diameter and 170 mm height for the casting of cylindrical fingers, **(c)** Castings Obtained

The stirring process was maintained for approximately 5 minutes following the addition of Al_2O_3 particles. Hexachloroethane (C_2Cl_6) was added to the alloy melt and allowed to pass through at a composite rate of 2-3 l/min for a duration of 3-4 minutes, after which the melt was well mixed. Permanent moulds were used to manufacture castings [21].

2.3 Scanning Electron Microscopy and EDS

The specimens were made ready according to the ASTM G69 standards (20 x 20 mm) and then cleaned, dried and etched. Also, were consequently mounted on uniquely planned specimen holder. The test specimen that was placed in this manner was seen at an accelerating voltage of 20 kV using a scanning electron microscope (SEM) built in the Czech Republic, TESCAN VEGA, 3 LMU. SEM observations of the particle dispersion that starts at a specific spot provided a general picture of the procedure that was carried out [22].

The elemental analysis was done by EDS 720 XRF Shimadzu. A thorough metallurgical assessment was produced by examining the combination of SEM and XRF analysis to assess the chemical composition and elemental study.

2.4 Static Weight Loss Corrosion Test

The corrosion behaviour of the alloy aluminium 2024 was investigated using immersion testing at various HCl concentrations. The casted material and matrix alloy were divided into 20 x 20mm pieces for the test using an abrasive cutting wheel. Vernier gauze was utilized to record the specimen dimensions, and an electronic balance was utilized to weigh the samples up to four decimal accuracy. They were submerged in solutions of 0.05N and 0.1N HCl and removed every 24 hours for a total of 96 hours. Following a dip in Clarke's solution and a little brushing to eliminate the corrosion product, the samples were lastly cleaned using distilled water and acetone prior to letting them air dry. The measurements of the corroded samples' weights were taken, and the rate of corrosion was expressed in mpy [23]. The mechanism primarily relies on the principle that the extent of corrosion can be quantified by the difference in weight before and after exposure to the corrosive environment.

2.5 Potentiodynamic Polarization Test

Rectangular samples (20 x 10 x 1 mm) were made ready by machining castings made of unreinforced metal and composite materials. Prior to conducting the studies, the specimens underwent the normal metallographic process as previously indicated.

Potentiodynamic polarization techniques were tested in 0.05N and 0.1N HCl medium. The experiments utilized the CH Instruments, USA model 608B series electrochemical analyzer/work station. In a 100 ml beaker, open-air electrochemical study was done using Ag/AgCl electrodes as the reference electrode and platinum electrodes as the counter electrodes (CE). A single square centimeter (1 x 1 cm) of the specimen was subjected to the corrosive environment. The measurements of polarization were conducted from the cathodic to the anodic direction, with the potential range set at ±200 mV from the OCP. The plot of E vs. log I was used to calculate the corrosion potential (Ecorr), anodic and cathodic Tafel slopes (ba & bc), and corrosion current density (Icorr) [24].

2.6 Stress corrosion test

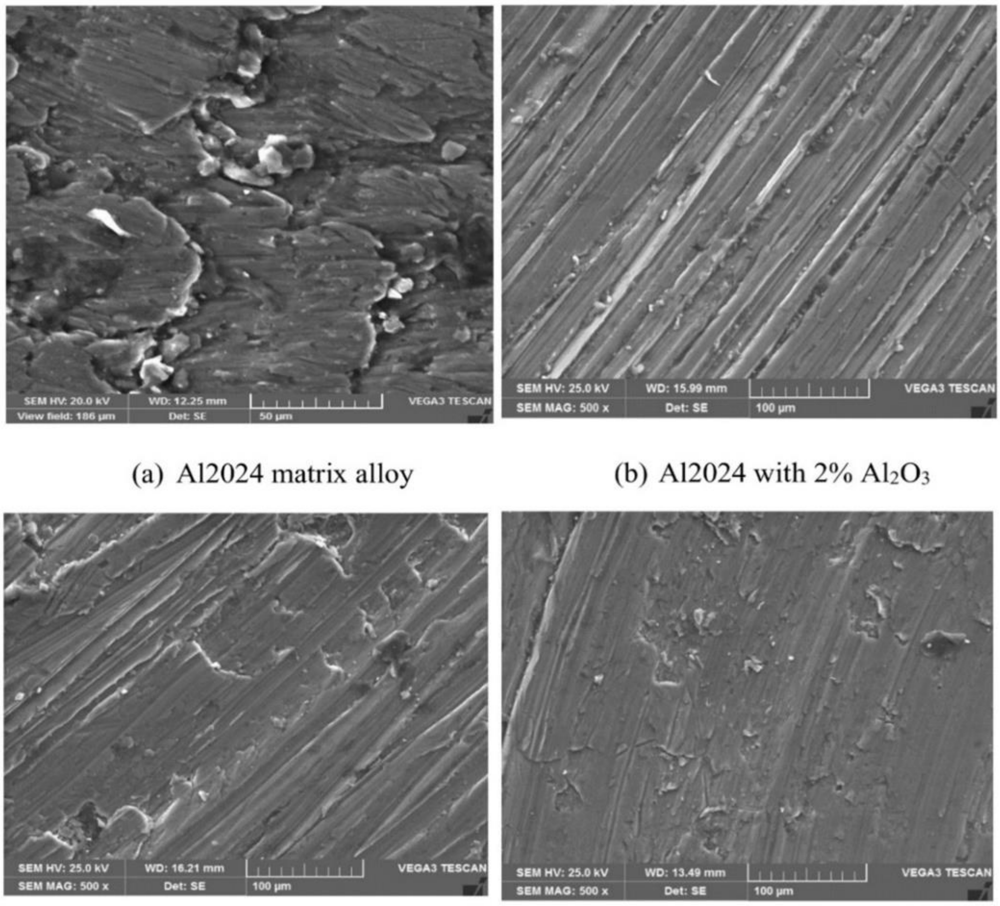
For stress corrosion testing, three-point-loaded specimens were made from the composites and the matrix alloy using the traditional metallographic method. These specimens were typically flat strips with dimensions of 150 mm long, 40 mm wide, and 8 mm thickness. Using an electronic balance, the specimens were subjected to weigh to the fourth decimal place prior to being put through the stress corrosion test.

Applications requiring high temperatures and pressure frequently employ autoclaves. The specimen was held up at both ends, and in the middle of the space between the end supports, a screw fitted with a ball to press against the specimen was used to apply bending stress. A prototype specimen with the same size and level of stress was utilized for calibration. Two liters of various HCl solution normalcy were produced and used as corrodent for each test. following the specimen's loading into the holder and autoclaving. After that, the autoclave was sealed and heated to a test temperature while the internal pressure increased. Tests with different temperature, normalcy, and durations of 10, 20, 30, 40, 50, and 60 minutes, respectively, were conducted on different composites with different percentages of reinforcement. After the corrosion test, the specimens were immersed in Clark's solution for 10 minutes and then gently scrubbed to remove any remaining scales. Next, the specimens were accurately weighed once more following their drying process. The corrosion rate was measured in milligrams per year (mpy) and converted to weight loss [25].

3. Result and Discussion

3.1 Morphological studies before corrosion test

Figures 2a-2d displayed scanning electron micrographs of each sample of the as-received composites. In all metal matrix composites, the particle distribution seems to be rather uniform. Because there was reduced porosity, there was improved interfacial bonding between the matrix and the reinforcing agents [26–27].



(a) Al2024 matrix alloy (b) Al2024 with 2% Al_2O_3

(c) Al2024 with 4% Al_2O_3 (d) Al2024 with 6% Al_2O_3

Figure 2. SEM images of **(a)** Al2024 alloy **(b)** Al2024 with 2% Al_2O_3 **(c)** Al2024 with 4% Al_2O_3 **(d)** Al2024 with 6% Al_2O_3

The surfaces of specimens made of pure aluminium were found to be rougher using a scanning electron microscope than specimens made of aluminium augmented with particles [28]. Increasing Al_2O_3 content in Al2024-Al_2O_3 composites enhances corrosion resistance due to improved microstructure. The results showed that the formation of Al, Mg, Cu and Oxygen was evident from the XRF quantitative analysis.

3.2 Static weight loss corrosion test

At different concentrations of HCl solutions, the weight loss corrosion rate of the matrix and composites was shown in Figures 4(a) and 4(b). Regardless of the reinforcing % and matrix, the corrosion rate dropped as exposure time increased. The study shows that the corrosion rate decreases with time because of the buildup of corrosion products inside the pit, which prevents further corrosion kinetics during extended immersion times. As the reinforcing concentration in all HCl solutions increased, the rate of corrosion reduced. The rate of corrosion in Al2024 with increase in weight percentage of Al_2O_3 resulted in increased oxygen concentrations which in turn led to thicker oxide films, enhancing corrosion resistance, although localized corrosion was observed in certain regions.

3.3 Morphological studies after corrosion test

Figures 5a-5d depicted the scanning electron microscopic analyses of the corroded surfaces of Al2024 matrix alloy and Al2024 / Al_2O_3 MMCs in 0.1N HCl after 96 hours of exposure. A small number of deep pits, flakes, and fractures that were perpendicular to the specimen's axis were visible in the micrographs. These cracks were created on the matrix alloy. However, there were fewer cracks visible on the surface of the reinforced composites and more extensive superficial pitting. On the other hand, as the proportion of Al_2O_3 reinforcement in Al2024 MMCs rised, fewer cracks appeared.

3.4 Potentiodynamic polarization studies

The obtained results for the potentiodynamic polarization tests conducted in different concentrated solutions of potassium chloride solution were shown below in the form of computer simulations.

Potentiodynamic polarization measurements were performed in various concentrations of HCl solutions in order to ascertain the impact of concentration on the corrosion and current density (I_{corr}) rate. Tafel polarization curves at 0.05N and 0.1N HCl solutions were shown for matrix alloy and composites in Figures 6 & 7. The corrosion rate increased as the concentration of corrosive media increased for all specimens, regardless of whether they were reinforced with Al_2O_3.

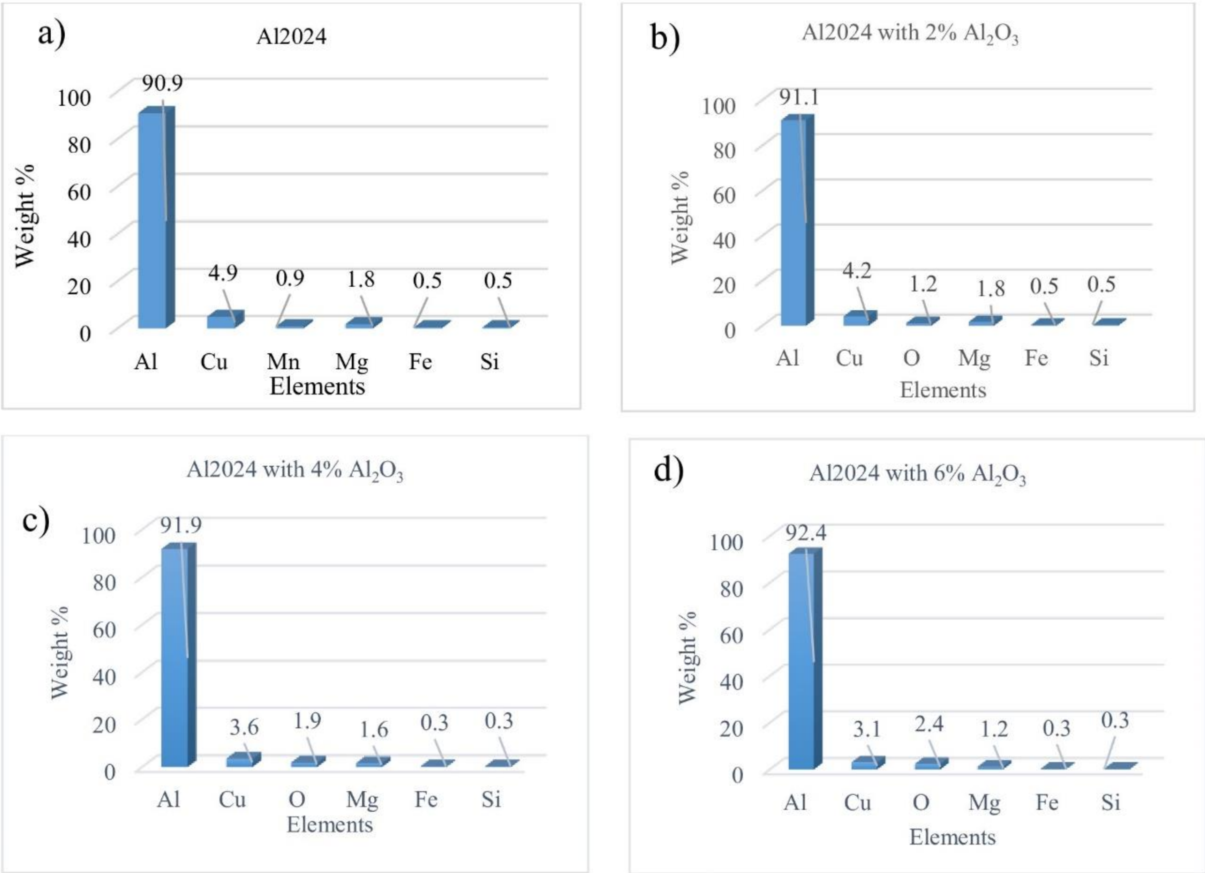


Figure 3. Quantitative XRF analysis of **a)** Al2024 **(b)** Al2024 with 2% Al_2O_3 **(c)** Al2024 with 4% Al_2O_3 **(d)** Al2024 with 6% Al_2O_3

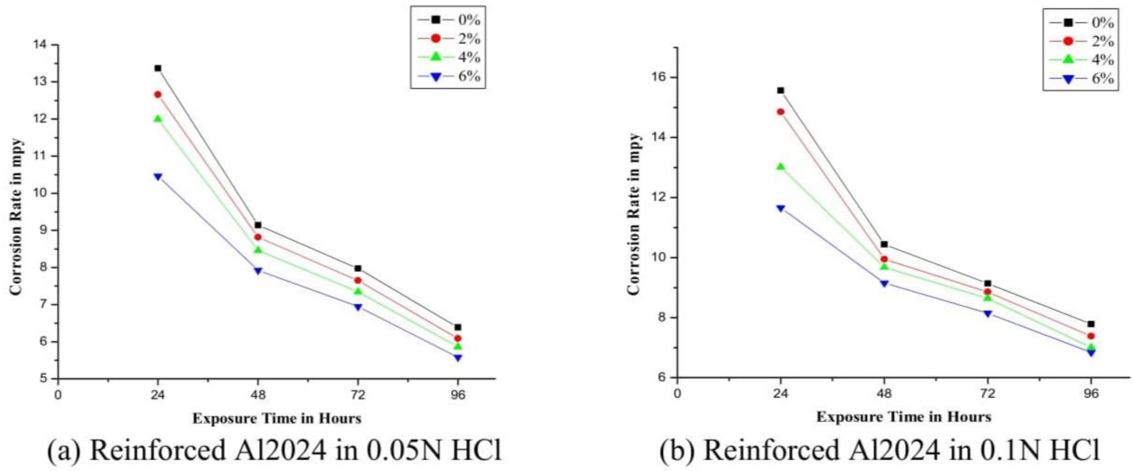
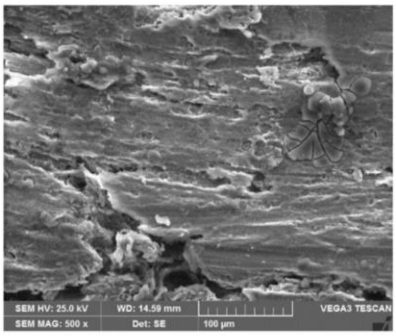
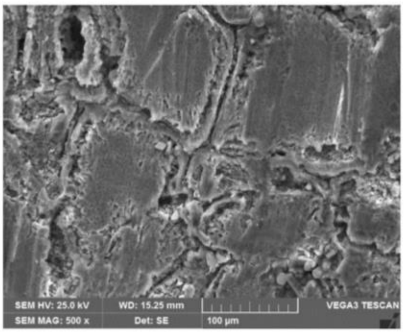


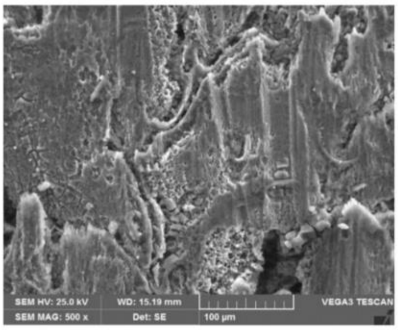
Figure 4. Effect of reinforcement on the rate of corrosion of Al2024 in (a) 0.05N HCl (b) 0.1N HCl



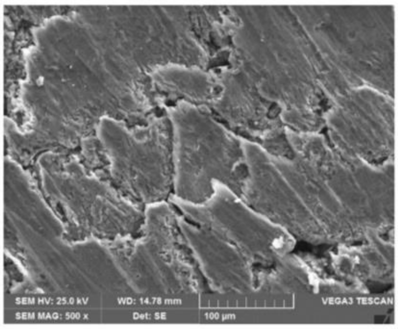
(a) Al2024 matrix alloy



(b) Al2024 with 2% Al_2O_3

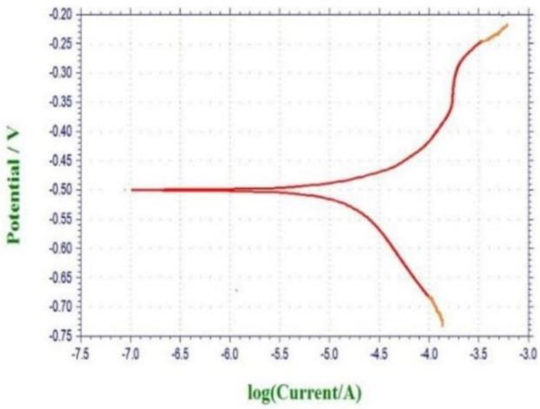


(c) Al2024 with 4% Al_2O_3

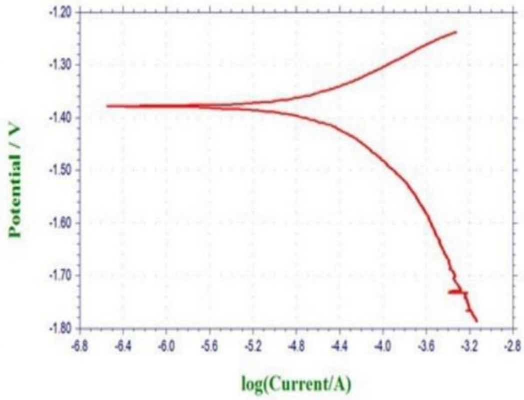


(d) Al2024 with 6% Al_2O_3

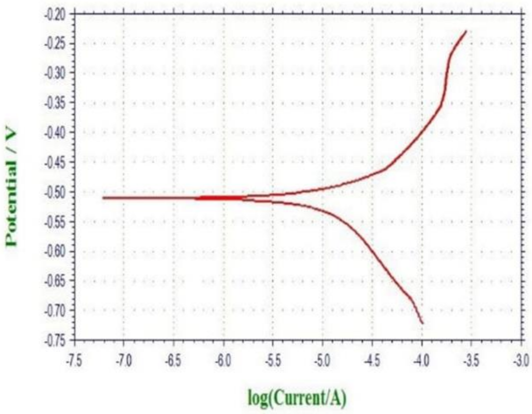
Figure 5. SEM images of **(a)** Al2024 alloy **(b)** Al2024 with 2% Al2O3 **(c)** Al2024 with 4% Al2O3 **(d)** Al2024 with 6% Al2O3 after weight loss corrosion test



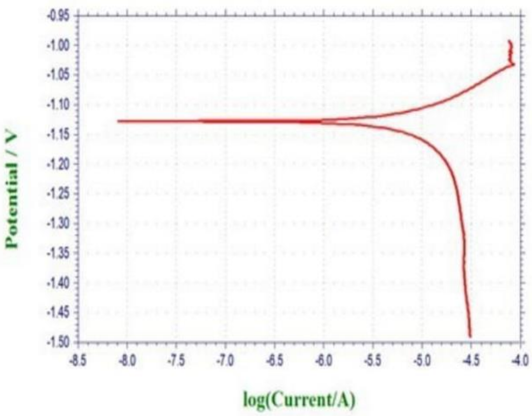
(a) Al2024 matrix alloy



(b) Al2024 with 2% Al_2O_3



(c) Al2024 with 4% Al_2O_3



(d) Al2024 with 6% Al_2O_3

Figure 6. Tafel plot of **(a)** Al2024 matrix alloy **(b)** Al2024 with 2% Al_2O_3 **(c)** Al2024 with 4% Al_2O_3 **(d)** Al2024 with 6% Al_2O_3 in 0.05N HCl solution

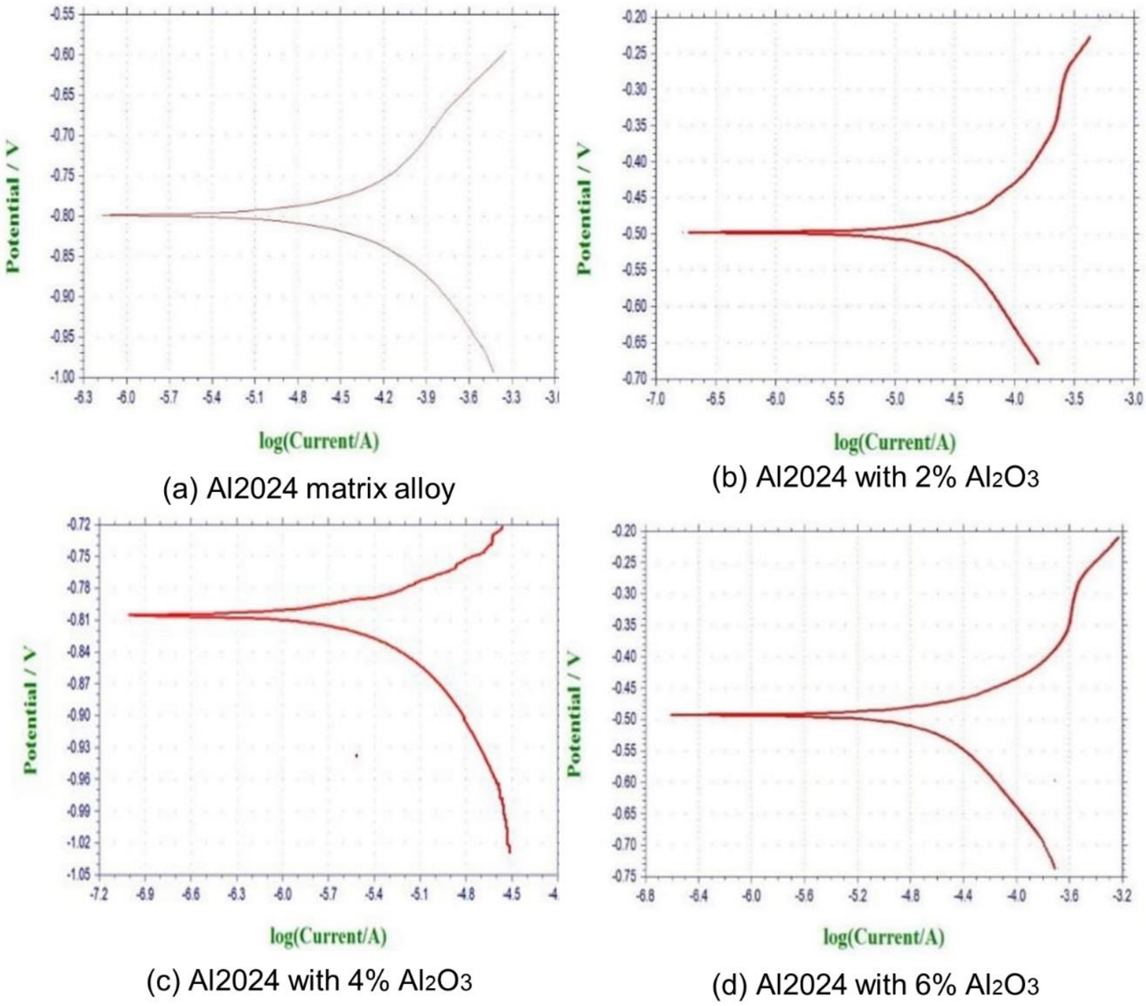


Figure 7. Tafel plot of **(a)** Al2024 matrix alloy **(b)** Al2024 with 2% Al_2O_3 **(c)** Al2024 with 4% Al_2O_3 **(d)** Al2024 with 6% Al_2O_3 in 0.1N HCl solution

Table 2. Potentiodynamic polarization studies of Al2024 / Al_2O_3 in HCl

Sl.No	Normality of HCl	Percentage of Al_2O_3	I_{corr}	Corrosion Rate (mpy)
1	0.05	0	3.697×10^{-5}	15.4043
		2	2.616×10^{-5}	10.9001
		4	2.572×10^{-5}	10.7168
		6	1.918×10^{-5}	7.9917
2	0.1	0	6.704×10^{-5}	27.9335
		2	6.213×10^{-5}	25.8877
		4	5.397×10^{-5}	22.4877
		6	5.158×10^{-5}	21.4918

The corrosion rate of each sample was significantly impacted by the normalcy. As demonstrated, the rate of corrosion likewise increased as normalcy increased. I_{corr}, or corrosion current density, is the point where the cathodic and anodic curves intersect. The conversion formula was used to calculate corrosion rate.

Corrosion rate in mpy = CE_wI_{corr}/d

Where C is the conversion constant (1.287×10^5), E_w is the equivalent weight of the sample (g), d is the density of the sample (gcm^{-3}). The corrosion rates and I_{corr} values of Al2024 / Al_2O_3 in HCl was tabulated in Table 2.

When the amount of Al_2O_3 particles increased, the corrosion rate decreased relative to the matrix alloy. Additionally, a modest decrease in hydrogen evolution was noticed when the weight fraction of the reinforcement increased.

3.5 Stress Corrosion test

The percentage of reinforcement that was added to the matrix alloy caused the corrosion rate to decrease [29]. Stress corrosion rate of Al2024 with and without reinforcement at 60 °C in 1N HCl was plotted against exposure time in Figure 8a. As exposure time increased, the rates of corrosion for both Al2024 and the matrix alloy, both with and without reinforcement, increased. In Figure 8b, the stress corrosion rate was plotted against various HCl concentrations at a temperature of 60 degrees Celsius and for a duration of 30 minutes. With an increase in HCl content, specimen stress corrosion rates increased. The corrosion rate decreased monotonically as the percentage of reinforcing content increased, as the figures clearly demonstrate. Or, to put it another way, corrosion resistance will increase with increasing reinforcing percentage.

In comparison to 0.05 N HCl solutions, the corrosion rates in 0.1N HCl were higher. This is because the corrodant's hydrogen concentration had increased. The parameters of corrosion were significantly influenced by temperature as well. The energy of hydrogen ion activation and the temperature change of the hydrogen gradient are two temperature-related parameters that affect the corrosion factor.

4. Conclusion

By using the liquid melt metallurgical process, Al2024 MMC reinforced with Al_2O_3 of 2, 4 and 6% weight percentage was created. The homogeneity of cast composites was confirmed by the homogeneous distribution of Al_2O_3, as shown by microstructural analysis.

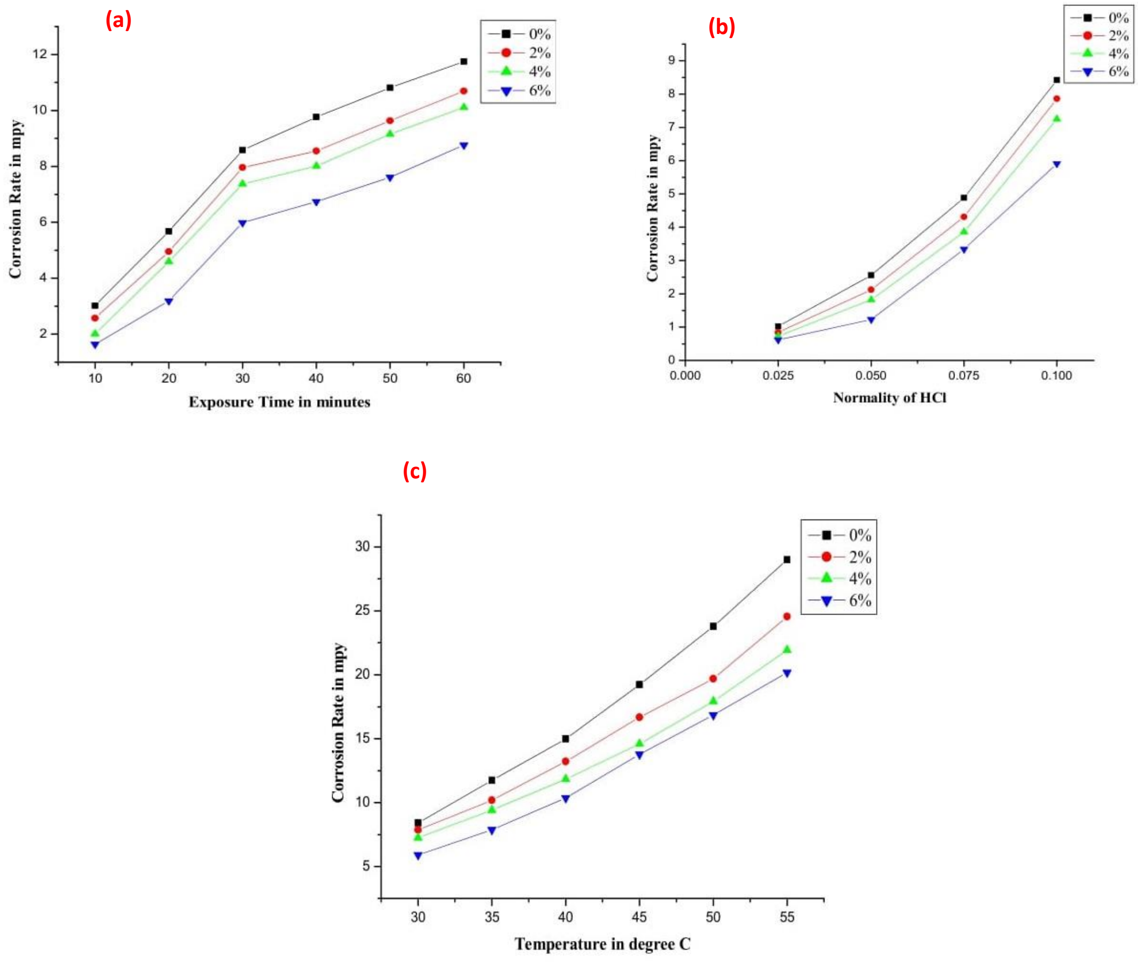


Figure 8. (a) Exposure time Vs corrosion rate at 600C in 0.1N HCl, **(b)** Normality Vs corrosion rate at 60 0C for 30 minutes, but mentioned as 600C, **(c)** Working temperature Vs corrosion rate in 0.1N HCl for 30 minutes exposure

According to the results of the static weight loss corrosion investigations, the corrosion rate of the Al2024 MMC reinforced with Al_2O_3 was found to be lower than that of the matrix alloy. The rate of corrosion increased as corrosive media concentration increased, according to potentiodynamic polarization research. Stress corrosion investigations on hybrid composites showed that the concentration of corrosive fluid, temperature, and exposure duration, increased the rate of stress corrosion of matrix alloy and reinforced composites. With an increase in reinforcing content, the amount of corrosion damage decreased, which could be because the alloy's tensile and bonding strengths were stronger. When it comes to Al2024, material loss due to corrosion was noticeably larger. Further research can be done with other reinforcing agent sizes to study the effect of reinforcing agent size on the corrosion behaviour of the composite.

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R. Lakshmi - Methodology, Investigation, Formal analysis, Data curation, Writing - Original Draft. H.R. Radha - Conceptualization, Supervision, Formal analysis, Data curation, Writing - Original Draft. P.V. Krupakara - Writing - Review & Editing. V. Latha - Writing - Review & Editing. P.V. Elumalai - Writing - Review & Editing. Ren Qiuying - Writing - Review & Editing. All the authors read and approved the final version of the manuscript.

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Competing Interests

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes