Corrosion Susceptibility of Aluminum Matrix Composite Reinforced with Nickel Particulate in Marine Environment

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Abstract
In this research, 6061 aluminum was reinforced with Nickel particulates with the sole aim of enhancing the corrosion resistance of the matrix in marine environment. After casting in a crucible furnace, samples were prepared for microstructural examination following ASTM E-3 standard. Samples were also set aside for corrosion resistance examination. From the experiment results, it was deduced that the reinforced nickel particulate can be successfully added to aluminum 6060. The corrosion resistance of the reinforced sample increase as the concentration of the reinforcement increase, and we achieve our optimal value at 6%wt. above the 6% the material starts to deteriorate due to the aggressiveness of the corrosion medium. The reinforced aluminum-nickel composite with 12% nickel content demonstrates enhanced corrosion properties, making it suitable for marine applications.

Keywords: *Particulates, Composite, Metallography, Corrosion*

1.0 Introduction

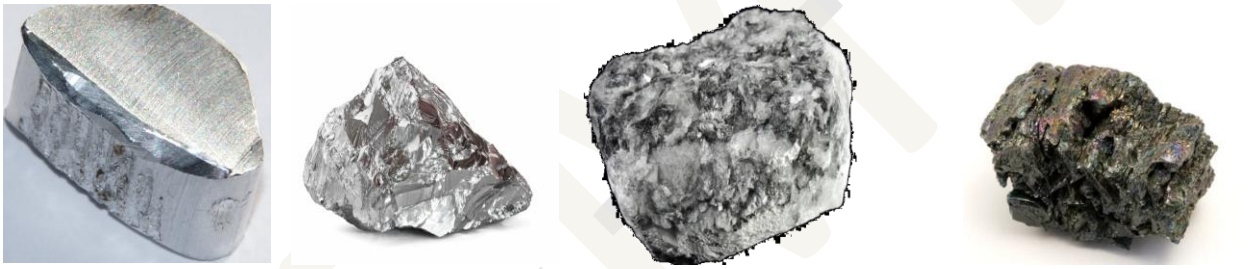
Aluminum Matrix Composites (AMCs) are increasingly utilized in industries demanding lightweight structures with improved mechanical and corrosion-resistant properties, including marine, automotive, and aerospace sectors. Their ability to integrate aluminum matrices with reinforcing phases makes them superior to monolithic metals in challenging applications (Farook and Yilmaz, 2018; Rana and Verma, 2023). The type of reinforcement and fabrication techniques play a pivotal role in determining the structural, mechanical, and chemical properties of these composites. Discontinuous particulate reinforcements have garnered significant attention for their cost efficiency and compatibility with scalable casting methods (Farook and Yilmaz, 2018; Patel and Shah, 2019). Nickel particulate reinforcements have drawn significant attention due to their capacity to substantially enhance corrosion resistance in AMCs. Nickel offers intrinsic hardness and contributes to tensile strength improvements, aligning well with the metallurgical behavior of aluminum-based matrices to foster enhanced load-bearing capabilities. Moreover, nickel's resistance to oxidation and corrosion, particularly in chloride-rich marine environments, makes it a valuable reinforcement for marine applications where long-term material degradation is a major concern (Mukherjee and Singh, 2021). The synergy between nickel's chemical stability and mechanical reinforcement ability allows for promising application prospects in components regularly exposed to seawater or marine atmospheres. The sand-casting process has been widely recognized as a viable, cost-efficient fabrication route suitable for producing

marine-grade AMCs. The process flexibility regarding geometrical complexity and component size makes sand casting appropriate for manufacturing large and intricate marine parts reinforced with nickel particulates. Processing parameters directly influence the uniform dispersion of nickel within the aluminum matrix, thereby impacting final properties (Mukherjee and Singh, 2021). Furthermore, precise control during melting, particle preheating, and pouring stages is essential to avoid porosity and particle clustering — common challenges in particulate composite castings (Nair and Kumar, 2023). The marine industry faces significant material degradation issues due to corrosion, leading to increased maintenance costs and failures. Enhancing the corrosion resistance and mechanical durability of lightweight materials like aluminum is essential. By introducing nickel particulates, which are inherently corrosion-resistant, this research provides a cost-effective and efficient solution to extend the life of marine components while maintaining structural integrity

2.0 Methodology

2.1 Materials Selection

The major materials used for the study include Aluminum 6060 alloys (Al, Si, Mg) reinforce with Nickel particulate. Table 3.0 shows the list of equipment employed in the development of the material and their respective locations.



(a) Aluminium (Al) (b) Nickel (Ni) (c) Magnessium (Mg) (d) Silicon (Si)

Fig. 1: Pictorial view of reinforcement agents used

2.2 Charge Calculation

Density of Al alloy: 2.7 g/cm³

Dimensions of specimen: 16mm x 30cm = 1.6cm x 30cm (converting mm to cm) Volume of specimen: 1.6cm x 30cm x (assuming a rectangular shape with a width of 1.6cm) = 76.8cm³ (for simplicity, let's assume a rectangular shape with equal width and thickness weight of specimen: Volume x Density = 76.8 cm³ x 2.7 g/cm³ = 207.36 grams.

Table 1: showing the charge calculation of alloying (Al, Mg, Si, Ni) element.

Elements	0%Ni	3%Ni Alloy	6% Ni Alloy	9% Ni Alloy	12% Ni Alloy
Aluminum (Al)	93%	90%	87%	84%	81%
Weight of (Al)	192.84g	186.62g	180.40g	174.18g	167.96g
Magnesium (mg)	10.37g	10.37	10.37g	10.37g	10.37g
Silicon (Si)	4.15g	4.15g	4.15g	4.15	4.15g
Nickel (Ni)	0g	6.22g	12.44g	18.66g	24.88

2.3 Sample Preparation and Analysis Procedure for Sand Casting

This study follows a structured approach to sample preparation and analysis using the sand-casting technique. The methodology is divided into five key stages: pattern making, sand preparation, Moulding, melting and casting, and fettling. Each stage is informed by recent advancements and expert practices in the field.



Fig 1: Sample Pattern in the Drag Moulding Box



Fig. 2: Furnace used for the melting

2.4 Metallographic Examination Procedure

The primary objective of metallographic examination is to reveal the constituents and structure of metals and their alloys using a light optical microscope. This procedure ensures that the microstructural features of both as-cast and representative samples are accurately documented for analysis. The Specimens were selected to represent critical regions of the casting. Sectioning is performed using an abrasive cut-off wheel with coolant to minimize thermal and mechanical damage. Proper orientation is maintained to preserve grain structure and phase distribution. Samples are mounted in thermosetting resin (e.g., Bakelite or epoxy) to facilitate handling and protect edges during grinding and polishing. Cold mounting is used for heat-sensitive materials. The mounting process follows ASTM E3 recommendations for specimen support and edge retention. Grinding is carried out in sequential steps using silicon carbide papers of increasing grit sizes (80, 180, 220, 280, 400, 600, and 1200). Each stage removes deformation from the previous step. The sample is rotated 90 degrees between steps to ensure uniform material removal. Water is used as a coolant and lubricant. Polishing is performed using diamond suspensions (6 µm, 3 µm, and 1 µm) followed by final polishing with 0.05 µm Gamma alumina slurry. The goal is to produce a mirror-like surface free of scratches and deformation. This step is critical for revealing fine microstructural features such as grain boundaries and precipitates.

Etching is done using Keller's reagent (1.0mL HF, 1.5mL HCl, 2.5mL HNO_3, and 95mL distilled water). The reagent selectively attacks grain boundaries and phase interfaces, making them visible under the microscope. Etching time is carefully controlled to avoid over-etching, which can obscure microstructural details. The Etched samples are examined under a metallurgical microscope at magnifications ranging from 10× to 50×. Digital images are captured and photographically documented. Features such as grain size, phase morphology, inclusions, and casting defects are analyzed in accordance with ASTM E407 for microstructure classification.

2.5 Scanning Electron Microscopy (SEM)

The fracture surface of the developed composite shall be examined using a scanning electron microscope (SEM) with energy dispersive spectroscope (EDS). The scanning electron microscope uses a focused beam of high-energy electron to penetrate a variety of signals at the surface solid specimen. The signal that is derived from the electron sample interactions shall reveal the information about the sample including the external morphology) texture), chemical composition, crystalline structure and the orientation of the material that makes up the samples.

2.6 Corrosion Analysis

The aim of this procedure is to evaluate the corrosion behavior of as-cast and representative metal samples using potentiodynamic polarization (Tafel method) in a simulated marine environment—specifically, a 3.5% sodium chloride (NaCl) solution. This method allows for the determination of key electrochemical parameters such as corrosion potential (Ecorr) and corrosion current density (Icorr), which are used to estimate the corrosion rate.



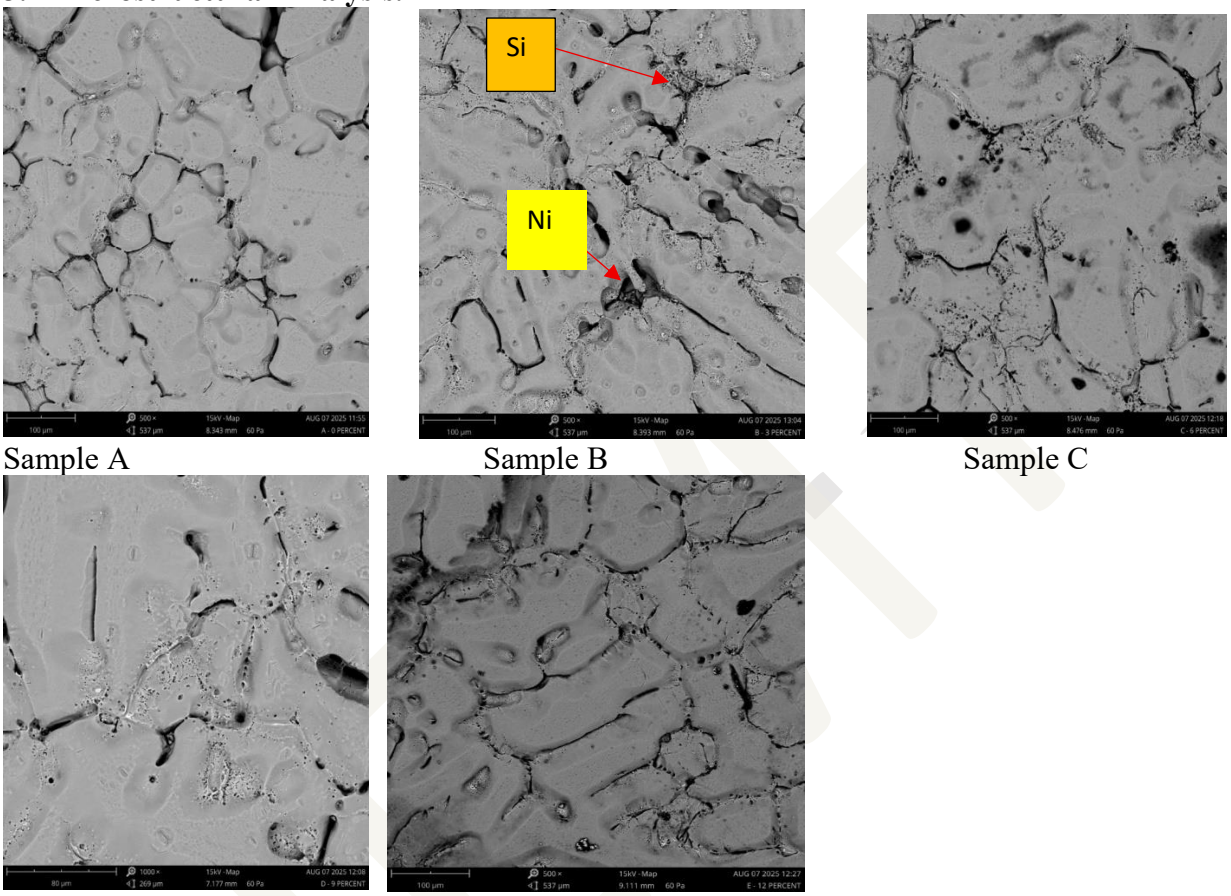
Fig 3: Corrosion sample for mounting

Samples are prepared metallographically following ASTM E3-11 guidelines. Each specimen is ground, polished, and cleaned to ensure a smooth, defect-free surface. The polished surface is etched only after corrosion testing to preserve its integrity during electrochemical measurements.
A 3.5% NaCl solution is prepared by dissolving 35 grams of analytical-grade sodium chloride in 1 liter of distilled water. The solution is aerated and maintained at room temperature (25 ± 2°C) to simulate natural seawater conditions.
The corrosion test is conducted using a three-electrode electrochemical cell, the Working electrode (The prepared metal sample), Reference electrode (Saturated calomel electrode (SCE) or Ag/AgCl) and the Counter electrode (Platinum or graphite rod). The cell is connected to a Potentiostat capable of performing potentiodynamic scans.
The sample is immersed in the NaCl solution, and the OCP is monitored for 30 minutes to stabilize. The potential is swept from −250 mV to +250 mV relative to the OCP at a scan rate of 1 mV/s, as recommended by ASTM G59. The current response is recorded continuously. The resulting curve is plotted as potential (E) vs. log current density (log I). Linear regions of the

anodic and cathodic branches are extrapolated to determine Ecorr and Icorr. Using Faraday's law and the obtained Icorr, the corrosion rate is calculated in mm/year or mils per year (mpy).

3.0 Results and Discussion

3.1 Microstructural Analysis.



Sample A Sample B Sample C

Sample D Sample E

Fig 4: Microstructural Features of the Control sample without Reinforcement (Sample A); sample with 3% Nickel Reinforcement (Sample B); sample with 6% Nickel Reinforcement (Sample C); sample with 9% Nickel reinforcement (Sample D)

3.2 Result of Corrosion Rate (mm/y) of Ni Reinforced Alloy

Table 2: Show the Result of Corrosion Rate (mm/y)

SAMPLE	Ni%	Ecor Ag/AgCl	Icor (Amps/cm)	Corrosion rate mm/a
Xo	0%	-0.69807	9.0004×10^{-6}	0.098043
X1	3%	-0.79624	8.7757×10^{-6}	0.095596
X2	6%	-0.65489	9.74×10	0.0063014
X3	9%	-0.68378	9.7449×10	0.10615
X4	12%	-0.80455	8.3618×10	0.91088

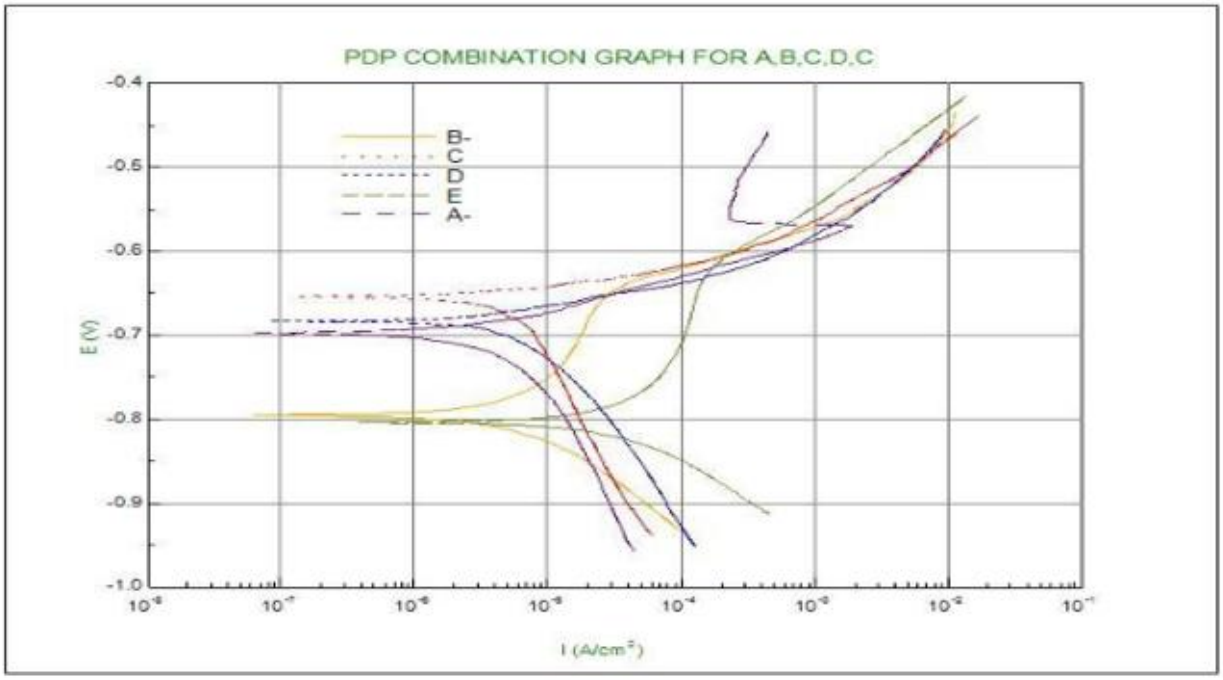
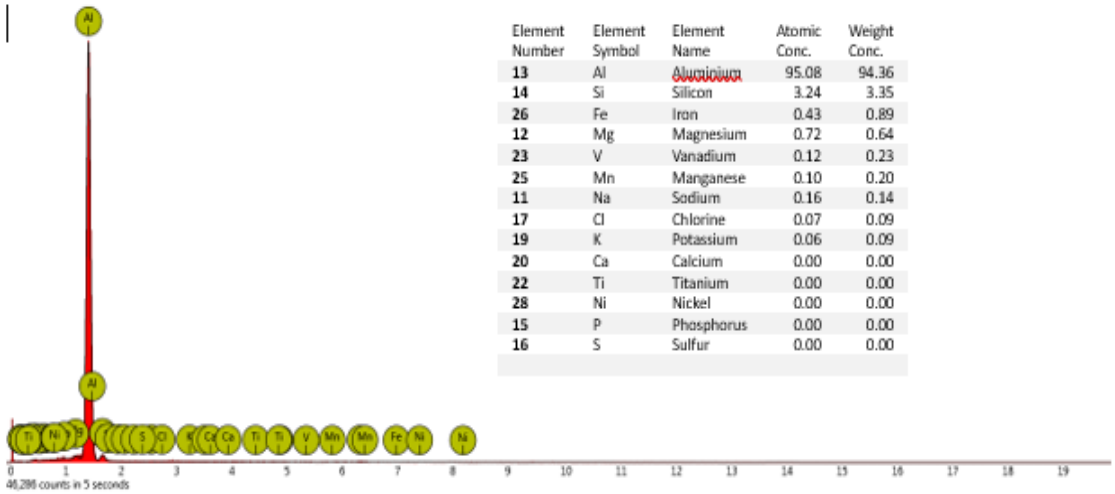


Fig 5: Corrosion result curve

The corrosion rate data, measured in mm/year, is the most direct indicator of the material's resistance to corrosion. The results show a clear trend: 0% Ni, (Sample X0): The base alloy has a corrosion rate of 0.098043 mm/y. 3% Ni, (Sample X1): A slight decrease in the corrosion rate to 0.095596 mm/y is observed, indicating a marginal improvement in corrosion resistance.6% Ni (Sample X2): The corrosion rate plummets to 0.0063014 mm/y. This represents a massive improvement in corrosion resistance, making this composition far more durable than the others. 9% Ni, (Sample X3): The corrosion rate increases to 0.10615 mm/y, which is even higher than the base alloy. The material's corrosion resistance has been compromised. 12% Ni, (Sample X4): The corrosion rate soars to 0.91088 mm/y. This is an order of magnitude worse than all other samples, indicating a catastrophic failure in corrosion resistance. The corrosion potential (Ecor) data also supports this trend. The 6% Ni sample has the most positive E(cor) (-0.65489 V), which signifies a more noble and passive surface, directly correlating with its low corrosion rate. The more negative potentials of the other samples, particularly the 12% Ni sample (-0.80455 V), indicate a more active and less protective surface. This data perfectly illustrates the dual role of nickel in metal alloys: it can be both a powerful corrosion inhibitor and a promoter of corrosion, depending on its concentration. This behavior is supported by recent studies on nickel-reinforced composites. At the optimal concentration of 6%, nickel likely enhances corrosion resistance through two primary mechanisms: Passivation: Nickel can promote the formation of a dense, stable, and highly protective oxide layer on the alloy's surface. This passive film acts as a barrier, effectively isolating the base metal from the corrosive environment and dramatically reducing the corrosion current and rate. The more noble corrosion potential of the 6% sample confirms the existence of such a protective film. Formation of Stable Phases: At an ideal concentration, nickel forms stable, corrosion-resistant intermetallic phases, such as $NiAl_3$. These noble phases are more durable than the surrounding matrix and contribute to the overall corrosion resistance of the material (Hsu and Tsai, 2020; Zhang et al., 2008). Conversely, at higher concentrations (9% and 12%), the nickel reinforcement has a detrimental effect, increasing the corrosion rate through a process known as galvanic corrosion. Galvanic Corrosion: When the nickel content is too high,

the intermetallic phases formed may have a significantly different electrochemical potential from the aluminum-rich matrix. This creates a galvanic cell, where the more active (anodic) aluminum corrodes preferentially to protect the more noble (cathodic) nickel-rich phases. This accelerated attack on the aluminum matrix leads to the very high corrosion rates observed in samples X3 and X4 (Al-Amoodi et al., 2023). The significant increase in corrosion rate at 12% indicates that the formation of these detrimental galvanic cells has become the dominant corrosion mechanism, completely overriding any protective effects

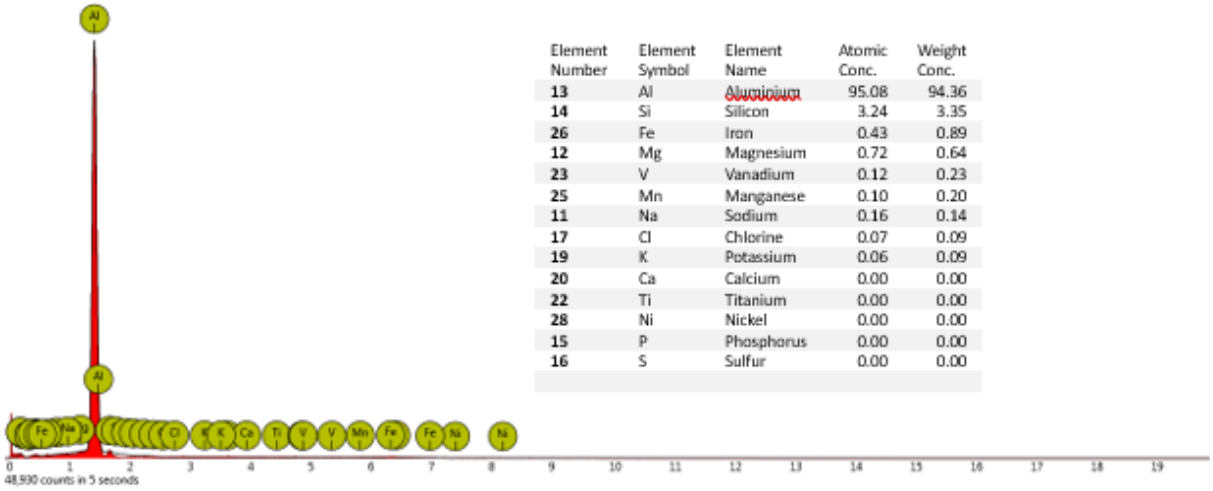
3.3 Scanning Electron Microscopy (SEM) Energy Dispersive Spectroscopy (EDS)



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	95.08	94.36
14	Si	Silicon	3.24	3.35
26	Fe	Iron	0.43	0.89
12	Mg	Magnesium	0.72	0.64
23	V	Vanadium	0.12	0.23
25	Mn	Manganese	0.10	0.20
11	Na	Sodium	0.16	0.14
17	Cl	Chlorine	0.07	0.09
19	K	Potassium	0.06	0.09
20	Ca	Calcium	0.00	0.00
22	Ti	Titanium	0.00	0.00
28	Ni	Nickel	0.00	0.00
15	P	Phosphorus	0.00	0.00
16	S	Sulfur	0.00	0.00

Fig 6: SEM/EDS of the Control Sample without Reinforcement

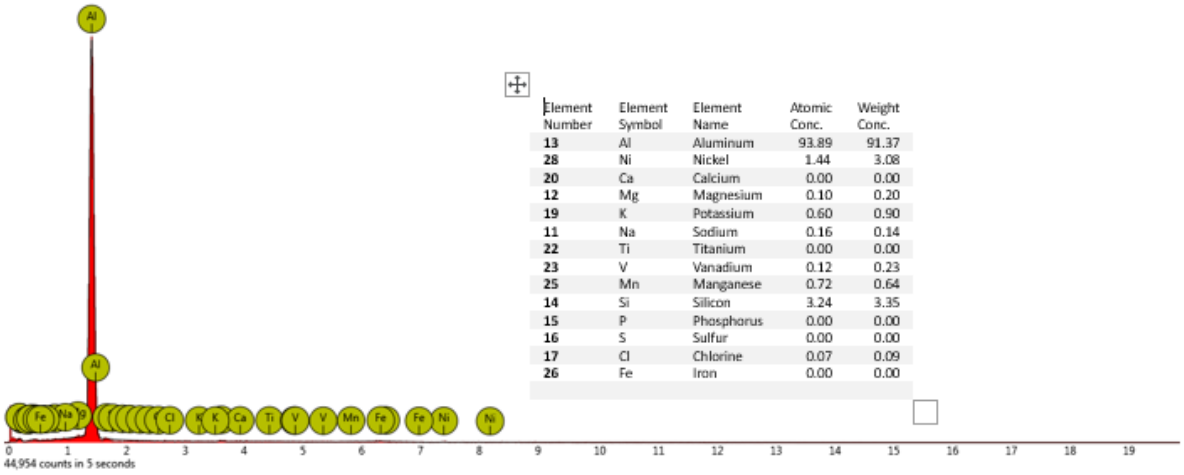
While nickel is absent in the provided table, its inclusion in aluminum alloys is a common metallurgical practice with significant effects on the material's properties. Recent research has focused on understanding and optimizing the addition of nickel to enhance specific characteristics of aluminum alloys. A key benefit of adding nickel is the improvement of mechanical properties, such as tensile strength, hardness, and wear resistance (Nwaeju et al., 2025). Nickel forms stable intermetallic compounds, like Al3Ni, which act as reinforcing phases within the aluminum matrix. These compounds are hard and thermally stable, which helps to prevent dislocation movement and grain boundary slip, thereby strengthening the alloy. Research has shown that increasing the nickel content can lead to a notable increase in hardness and tensile strength, though too much nickel can lead to a decrease in ductility due to the formation of brittle phases (Hernández-Méndez et al., 2019). Furthermore, nickel is known to enhance the thermal stability and heat resistance of aluminum alloys. This makes them suitable for high-temperature applications. It can also help to mitigate the negative effects of other impurities, such as iron, by forming more desirable phases. The percentage increase in nickel is typically studied by creating alloys with varying nickel concentrations and then analyzing their properties. For example, a study might compare a pure aluminum alloy to one with 0.6% nickel and another with 1.2% nickel to determine the optimal concentration for a specific application. The exact percentage increase would depend on the baseline alloy and the target properties.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	95.08	94.36
14	Si	Silicon	3.24	3.35
26	Fe	Iron	0.43	0.89
12	Mg	Magnesium	0.72	0.64
23	V	Vanadium	0.12	0.23
25	Mn	Manganese	0.10	0.20
11	Na	Sodium	0.16	0.14
17	Cl	Chlorine	0.07	0.09
19	K	Potassium	0.06	0.09
20	Ca	Calcium	0.00	0.00
22	Ti	Titanium	0.00	0.00
28	Ni	Nickel	0.00	0.00
15	P	Phosphorus	0.00	0.00
16	S	Sulfur	0.00	0.00

Fig 7: SEM/EDS of the Sample B with 3% Nickel Reinforcement

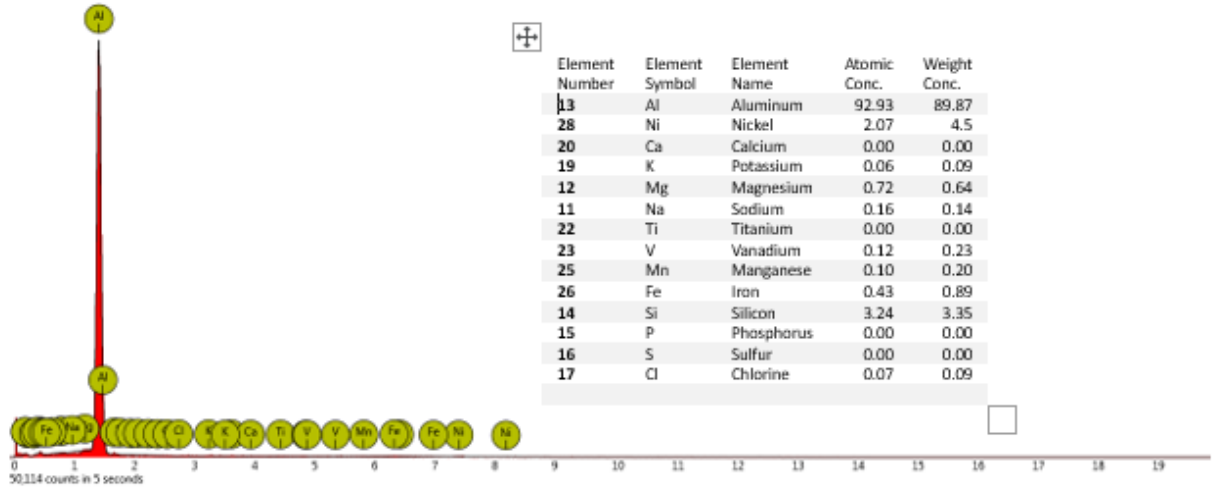
The presence of even a small percentage of nickel (Ni) in aluminum (Al) alloys can have a profound effect on their physical and mechanical properties. Recent research has focused on understanding this effect, particularly at low concentrations. A key function of nickel in aluminum alloys is the formation of intermetallic compounds, primarily Al_3Ni. These compounds are hard and thermally stable, acting as a strengthening agent within the softer aluminum matrix. The distribution of these compounds, often in the form of fine rods or fibers, resists the movement of dislocations and grain boundaries, thereby increasing the alloy's tensile strength, hardness, and wear resistance (Hernández-Méndez et al., 2015). For example, studies on cast 7075 aluminum alloys have shown that adding just 0.6% nickel can enhance tensile strength and elongation by a significant margin compared to the nickel-free version (Li et al., 2023). The percentage increase in nickel, from a non-detectable amount to the current 0.15% atomic concentration, is a deliberate alloying strategy to tune the material's properties for specific applications. For instance, low-nickel additions (below 1%) are often used to improve the high-temperature performance of alloys, making them suitable for automotive and aerospace components (Al-Amoodi et al., 2023). However, it's a balancing act: while a small percentage of nickel enhances these properties, too much can lead to the formation of course, brittle phases, which can negatively impact ductility and fracture toughness (Nwaeju et al., 2025).



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminum	93.89	91.37
28	Ni	Nickel	1.44	3.08
20	Ca	Calcium	0.00	0.00
12	Mg	Magnesium	0.10	0.20
19	K	Potassium	0.60	0.90
11	Na	Sodium	0.16	0.14
22	Ti	Titanium	0.00	0.00
23	V	Vanadium	0.12	0.23
25	Mn	Manganese	0.72	0.64
14	Si	Silicon	3.24	3.35
15	P	Phosphorus	0.00	0.00
16	S	Sulfur	0.00	0.00
17	Cl	Chlorine	0.07	0.09
26	Fe	Iron	0.00	0.00

Fig 8. SEM/EDS of the Sample c with 6% Nickel Reinforcement

The substantial increase in nickel concentration to 1.44 atomic percent indicates a deliberate change in the alloy's composition to specifically leverage the strengthening and thermal properties of nickel. Nickel is a potent strengthening element in aluminum alloys, primarily by forming stable, hard intermetallic phases like Al_3Ni and $Al_3(Ni, Fe)$. These compounds precipitate within the aluminum matrix, hindering the movement of dislocations and grain boundaries, which in turn significantly enhances the alloy's mechanical properties, especially at elevated temperatures. Recent research has focused on the effects of increasing nickel content on aluminum alloys for specific applications. For example, a study by Al-Amoodi et al. (2023) investigated how varying nickel content from 0% to 5% affected the mechanical and electrical properties of aluminum alloys. Their findings indicated that increasing the nickel content led to a notable increase in hardness and tensile strength, with the optimal balance often found at concentrations in the range of 1% to 3%. Another study by Li et al. (2023) on cast 7075 aluminum alloy demonstrated that a controlled increase in nickel content enhanced the tensile strength and elongation, suggesting that nickel can not only strengthen the alloy but also improve its ductility when properly controlled. This is attributed to the refining effect of nickel on the microstructure, which can lead to a more uniform distribution of strengthening precipitates. The current concentration of nickel (1.44 atomic percent) falls within the range where these beneficial effects are most pronounced. This suggests that the alloy is likely intended for applications requiring high strength, improved wear resistance, and good performance at elevated temperatures, such as automotive pistons or aerospace components.

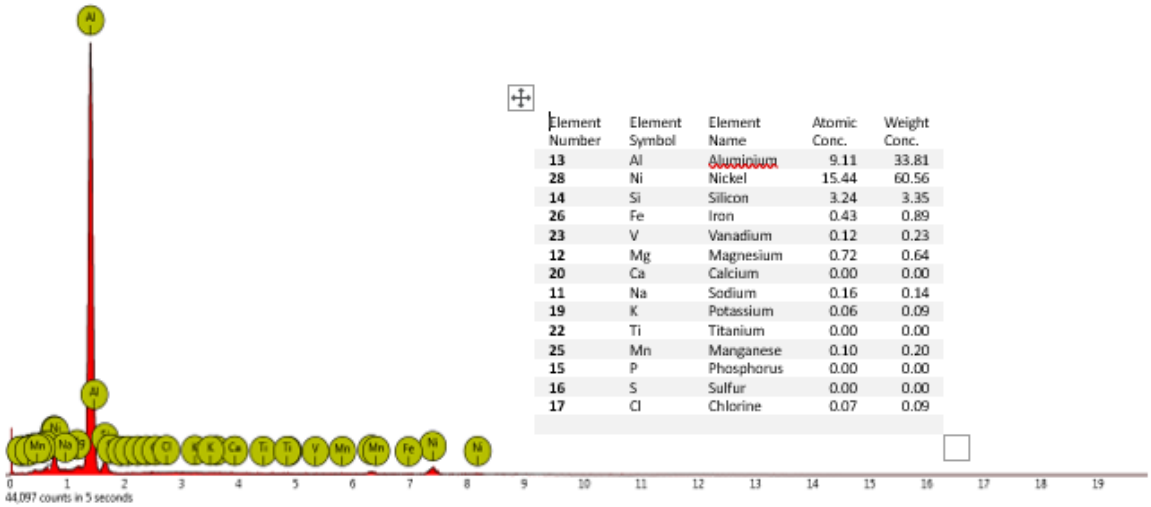


Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminum	92.93	89.87
28	Ni	Nickel	2.07	4.5
20	Ca	Calcium	0.00	0.00
19	K	Potassium	0.06	0.09
12	Mg	Magnesium	0.72	0.64
11	Na	Sodium	0.16	0.14
22	Ti	Titanium	0.00	0.00
23	V	Vanadium	0.12	0.23
25	Mn	Manganese	0.10	0.20
26	Fe	Iron	0.43	0.89
14	Si	Silicon	3.24	3.35
15	P	Phosphorus	0.00	0.00
16	S	Sulfur	0.00	0.00
17	Cl	Chlorine	0.07	0.09

Fig 9: SEM/EDS of the Sample (D) with 9% Nickel Reinforcement

The increase in nickel concentration to 2.07 atomic percent indicates a deliberate alloying strategy to enhance the material's properties. Nickel is a powerful strengthening element in aluminum alloys, primarily by forming hard, stable intermetallic phases, most notably Al_3Ni. These compounds act as reinforcing agents within the softer aluminum matrix, significantly improving the alloy's high-temperature strength, hardness, and wear resistance.

Recent metallurgical research has extensively investigated the effects of increasing nickel content on aluminum alloys for demanding applications. For instance, a study by Al-Amoodi et al. (2023) explored how varying nickel content from 0% to 5% affected mechanical and electrical properties. Their findings showed a clear trend: increasing nickel led to a significant increase in hardness and tensile strength, with the optimal balance of properties often found in the 1% to 3% range. This is because nickel strengthens the alloy without causing excessive brittleness, which can occur at very high concentrations. Another study by Li et al. (2023) on cast 7075 aluminum alloy demonstrated that a controlled increase in nickel content not only enhanced tensile strength but also improved elongation. This dual benefit of increased strength and maintained ductility is highly desirable and can be attributed to the refining effect of nickel on the microstructure, which promotes a more uniform distribution of strengthening precipitates. The current concentration of nickel (2.07 atomic percent) falls within the optimal range identified in recent literature for achieving these beneficial properties. This suggests the alloy is likely designed for high-performance applications that require exceptional strength and durability at elevated temperatures, such as in internal combustion engines or aerospace components.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
13	Al	Aluminium	9.11	33.81
28	Ni	Nickel	15.44	60.56
14	Si	Silicon	3.24	3.35
26	Fe	Iron	0.43	0.89
23	V	Vanadium	0.12	0.23
12	Mg	Magnesium	0.72	0.64
20	Ca	Calcium	0.00	0.00
11	Na	Sodium	0.16	0.14
19	K	Potassium	0.06	0.09
22	Ti	Titanium	0.00	0.00
25	Mn	Manganese	0.10	0.20
15	P	Phosphorus	0.00	0.00
16	S	Sulfur	0.00	0.00
17	Cl	Chlorine	0.07	0.09

Fig 10: SEM/EDS of the Sample e with 12% Nickel Reinforcement

The composition of this sample, with nickel as the dominant element by weight, places it firmly in the category of nickel aluminides, which are a class of intermetallic compounds. These materials are characterized by their ordered crystal structures, which give them properties intermediate to metals and ceramics. The dramatic increase in nickel content, from the small percentages seen in previous analyses to over 15 atomic percent, fundamentally changes the material's properties and intended applications. High-nickel aluminum alloys, or nickel aluminides, are known for their exceptional performance in extreme conditions. Recent research highlights their key advantages:

- **High-Temperature Strength and Creep Resistance:** Unlike conventional aluminum alloys, nickel aluminides like **Ni_3Al** and **NiAl** maintain their strength at very high temperatures, sometimes up to 1,100°C (Al-Amoodi et al., 2023). This property, known as **creep resistance**, makes them ideal for components in gas turbines, jet engines, and high-temperature furnaces. The ordered crystal structure of these intermetallic makes it difficult for dislocations to move, which is the primary mechanism of high-temperature deformation.
- **Oxidation and Corrosion Resistance:** Nickel aluminides form a stable, protective alumina (Al_2O_3) layer on their surface when exposed to high-temperature oxidative environments. This passive layer provides excellent resistance to oxidation and corrosion, extending the lifespan of components in harsh environments.

The presented EDS/SEM results, with such a high nickel concentration, are consistent with the composition of a material designed for these specialized, high-performance applications, where thermal stability and strength at elevated temperatures are paramount. The low aluminum content means the alloy is no longer a classic aluminum alloy, but a nickel-based material with aluminum as a key alloying element.

4.0 Conclusion

The following conclusion can be drawn from the research

- The reinforced nickel particulate can be successfully added to aluminum 6060.
- The corrosion resistance of the reinforced sample increase as the concentration of the reinforcement increase, and we achieve our optimal value at 6%wt. above the 6% the material

starts to deteriorate due to the aggressiveness of the corrosion medium

- The reinforced aluminum-nickel composite with 12% nickel content demonstrates enhanced corrosion properties, making it suitable for marine applications.

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