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Numerical and Experimental Investigation of Galvanic Corrosion in Coupled AA7025 and SS304L for Marine Applications

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Abstract

This study investigates the galvanic corrosion of AA7025 aluminum alloy coupled with 304L stainless steel (SS) fasteners in marine structures, using a multi-methodological approach involving analytical modeling, SolidWorks 3D modeling, COMSOL Multiphysics simulations, and experimental validation. The AA7025-304L SS couples were tested in tap water, 3.5% NaCl, and 1M H₂SO₄ for 30 days. Corrosion rates increased significantly due to galvanic coupling: 4.92× in tap water, 3.16× in NaCl, and 4.26× in H₂SO₄, with predictive models accurate within 5% error. H₂SO₄ caused the highest hardness loss (10.97%) and a corrosion depth of 100.4 μm. Microstructural analysis showed CaCO₃ scaling in tap water, severe pitting in NaCl, and generalized dissolution in H₂SO₄. COMSOL simulations identified an Al-5Zn sacrificial anode as an effective mitigation strategy, providing a protective current density of 0.84 A/m² and a polarization potential of -1.08 V, significantly reducing AA7025 corrosion in marine-relevant environments.

Keywords: aluminum alloy; stainless steel; galvanic corrosion; COMSOL Multiphysics; marine environment; cathodic protection.

Introduction

Aluminum alloys are indispensable in modern engineering due to their high strength-to-weight ratio, excellent conductivity, and recyclability [1,2], making them crucial for the aerospace, automotive, and marine industries [3]. The 7xxx series alloys, primarily alloyed with zinc, offer the highest strength among aluminum alloys, with properties comparable to some steels, which is critical for demanding structural applications [4,5]. Among these, AA7025 is valued for its mechanical properties and weldability. However, its application, particularly in marine environments, is challenged by its susceptibility to localized corrosion, such as pitting and stress corrosion cracking (SCC) [6,7].

The necessity for lowering the weight of ships, increasing payloads, and reducing fuel consumption has increasingly turned shipbuilders toward aluminum alloys. Compared with low-carbon steels, Al alloys have the potential to reduce the weight of ship structures by up to 50% (Feng et al., 2022). However, when exposed to marine environments, overcoming the corrosion caused by saline water poses a major challenge. Metals exist in nature in relatively stable forms like oxides, sulfides, or salts, making their elemental metal surfaces thermodynamically unstable and prone to spontaneous electrochemical degradation (Feng et al., 2022). External factors—such as medium composition, temperature, pressure, pH, and mechanical stress—alongside internal factors like crystal form and surface morphology, heavily dictate these varying corrosion processes (Zhang et al., 2023).

The engineering life of aluminum and its alloys is fundamentally limited by their corrosion performance, which causes premature failure through the loss of structural integrity. Corrosion typically initiates as microscopic pits that subsequently grow into macroscopic failures, among which environmentally assisted cracking (EAC) is particularly detrimental to mechanical breakdown and fatigue life (Connolly et al., 2023). In service, corrosion is heavily accelerated by environmental factors such as road deicing salts, high humidity, and seawater chemistry. Seawater consists of complex saline solutions containing dissolved oxygen (ranging from 4 to 8 mg/L depending on temperature and depth) (Granata, 2020). Furthermore, atmospheric corrosion in marine environments is driven by the combined action of sunshine, temperature, and rain, where high humidity and elevated salinity lead to severe dew condensation and the long-term deposition of surface salt layers that continuously aggravate localized alloy degradation (Cao et al., 2018).

A critical and often overlooked aspect of structural design alongside these environmental challenges is the interaction between the primary alloy and its fasteners [8]. Real-world structures involve thousands of mechanical joints, which serve as preferential sites for corrosion due to dissimilar material coupling [8]. The coupling of AA7025 aluminum alloy with more noble materials like 304L stainless steel (SS) fasteners creates a galvanic cell where the aluminum alloy acts as the anode and undergoes accelerated corrosion [9]. While research has focused on enhancing intrinsic corrosion resistance through alloying, heat treatments, and coatings [10,11], most of the existing literature focuses broadly on general aluminum and stainless steel interactions without addressing specific mesoscale galvanic morphologies or localized bolted-assembly lifetimes using advanced software.

To the best of our knowledge, there is presently no documented investigation into the impact of SS304L stainless steel fasteners on the microstructure and durability of AA7025 aluminum alloy across these corrosive environments, nor has the galvanic corrosion behavior within this specific configuration been addressed using COMSOL Multiphysics software. To address this significant knowledge gap, this study provides a comprehensive investigation into the corrosion mechanisms and mechanical degradation of AA7025 when mechanically coupled with 304L SS fasteners [9]. We examine the performance of this galvanic couple in three distinct aqueous environments: Hora Harsade lake tap water, simulated seawater (3.5% NaCl), and an accelerated acidic environment. By integrating analytical modeling, SolidWorks 3D modeling, COMSOL Multiphysics simulations [12], and rigorous experimental validation—including weight loss (ASTM G31), Vickers microhardness (ASTM E384), environmental mapping via MATLAB, and advanced microstructural characterization (OM, SEM/EDS, XRD, FTIR)—this work quantifies the acceleration of corrosion, elucidates the underlying failure mechanisms, and offers validated predictive models. The findings establish crucial guidelines for material selection and introduce effective mitigation strategies, such as the optimization of sacrificial anodes, to extend the service life of these critical engineering structures.

Methods

Materials and Corrosive Environments

As shown in (Table 1) and (Table 2), the materials AA7025 coupons (40×40×4 mm) and 304L SS fasteners (Ø10×120 mm) were used. The three corrosive environments were: Sourced from Hora Harsade Lake, Ethiopia (TDS: 1110 mg/L, pH: 8.81, Conductivity: 2220 µS/cm), Saline Solution: 3.5% (w/v) NaCl in deionized water to simulate a marine environment, and Acidic Solution: 1M H₂SO₄ in deionized water to simulate acid rain were used.

Table 1. Elemental composition of AA7025 aluminum alloy (wt.%)

Si	Cu	Mg	Fe	Zn	Others	Al
0.13	0.57	0.90	0.21	3.18	0.31	94.7

Table 2. Elemental composition of 304L stainless steel (wt.%)

C	Cu	Mn	Ni	Cr	Others	Fe
0.054	0.72	1.81	8.75	20.27	1.096	67.3

Sample Preparation

The specimens were prepared in accordance with the general recommendations of ASTM G31-71 for laboratory immersion corrosion testing. The size and shape of the specimens were selected according to the objectives of the study, the nature of the materials, and the requirements of the experimental apparatus. AA7025 aluminum alloy specimens and 304L stainless-steel fasteners were prepared for exposure to three corrosive environments: Hora Harsade water, 3.5% NaCl solution, and 1 M H₂SO₄ solution.

The prepared specimens were used for weight-loss measurements, hardness testing, and microstructural and corrosion-product characterization using optical microscopy, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDS), Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD). Since the preparation requirements differ among the analytical techniques, the procedures were grouped according to the type of specimen and analysis.

Specimen Preparation for Corrosion Exposure

The AA7025 specimens were prepared to the required dimensions and surface condition for the experimental configuration. The specimens were cleaned to remove contaminants associated with cutting, machining, and handling before exposure. The 304L stainless-steel fasteners were prepared separately and used either independently or in galvanic contact with AA7025 according to the experimental group configuration. The specimens were then assigned to the six experimental groups according to the exposure environment and coupling condition. The corresponding experimental configurations are illustrated in Fig.1.

The geometric surface areas of the components were calculated from their measured dimensions. The anode assembly consisted of rectangular AA7025 plates and a hollow shaft, whereas the cathode consisted of solid shafts connecting the plates. The calculated dimensions and surface areas are presented in Table 3.

Table 3. Geometric dimensions and calculated surface areas of the anode and cathode components

Component	Quantity	Dimensions (mm)	Surface-area expression	Surface area (mm ²)
Rectangular Plate 1 (Anode)	2	H = 120, L = 45, T = 3	$(2(LH+HT+LT))$	23,580
Rectangular Plate 2 (Anode)	2	H = 120, L = 1, T = 3	$(2(LH+HT+LT))$	1,932
Hollow Shaft (Anode)	1	L = 120, (Ro) = 2.5, (Ri) = 2	$2\pi RoL+2\pi RiL+2\pi(Ro^2-Ri^2)$	3,407.06
Total Anode Surface Area	—	—	—	28,919.06
Solid Shaft (Cathode)	1	L = 120, r = 2	$2\pi rL+2\pi r^2$	1,533.09

Metallographic and Surface Characterization

Specimens intended for optical microscopy and scanning electron microscopy were prepared to provide suitable surfaces for examination of the microstructure and corrosion morphology. For optical microscopic examination, the specimens were initially ground using P240 silicon carbide paper to remove saw marks and produce a relatively level surface. Intermediate polishing was performed using a polishing cloth to remove deeper scratches generated during grinding. Final polishing was performed using a 1 μm diamond slurry on a soft pad to obtain a smooth, mirror-like surface.

The polished specimens selected for optical microscopy were subsequently etched using Keller's reagent to reveal grain boundaries and other microstructural features. After etching, the specimens were rinsed and dried before microscopic examination. The prepared surfaces were examined using optical microscopy to evaluate the grain structure, precipitates, and surface imperfections.

For SEM/EDS examination, specimens after corrosion exposure were prepared to preserve the corrosion morphology and corrosion products formed on the exposed surfaces. The surfaces were examined using scanning electron microscopy to characterize morphological features such as pits, cracks, surface deposits, and corrosion-product layers. Energy-dispersive X-ray spectroscopy was used to determine the elemental composition of selected surface regions and to assist in identifying elements associated with the corrosion products and localized corrosion processes.

Thus, optical microscopy was primarily used for examination of the prepared metallographic microstructure, whereas SEM/EDS was used for higher-resolution examination of the exposed and corroded surfaces and their associated elemental composition.

Powder Sample Preparation for FTIR and XRD

Corrosion products formed on the exposed metal surfaces were collected for FTIR and XRD characterization. The corrosion material was carefully removed from the exposed surfaces, ensuring that the collected material represented the corrosion products formed during the

respective exposure conditions. The collected material was dried and, where required, ground into a fine powder before analysis.

For FTIR characterization, the prepared corrosion-product powder was used for spectral analysis. Depending on the measurement configuration, the powder was prepared for placement on the ATR crystal or for transmission measurement using an appropriate sample preparation procedure. The FTIR spectra were used to identify characteristic absorption bands associated with the functional groups and chemical compounds present in the corrosion products. The observed absorption bands were interpreted by comparison with reference spectral data.

For XRD characterization, the collected corrosion products were finely ground to obtain a relatively homogeneous powder suitable for diffraction analysis. The powder was loaded into the sample holder and leveled to obtain a flat and uniform surface before measurement. The resulting diffraction patterns were analyzed and compared with reference diffraction data to identify the crystalline phases formed during corrosion exposure.

The use of powdered corrosion products for FTIR and XRD allowed the chemical and crystalline characteristics of the corrosion products formed under the different exposure environments to be evaluated.

Sample Preparation and Vickers Micro hardness Testing

The specimens used for hardness testing were prepared according to the requirements of the Vickers micro hardness testing equipment. The hardness measurements were performed after the specimens had been subjected to the respective corrosive environments for the prescribed exposure durations. The specimen number and experimental group were considered during the hardness measurements to ensure that the results represented the respective exposure conditions.

A Vickers micro hardness tester was used to evaluate the hardness of AA7025. A square-pyramidal diamond indenter with a face angle of 136° was applied using a nominal load of 1 gf and a dwell time of 10 s. five indentations were produced at different locations on each specimen to obtain representative hardness measurements.

The two diagonals of each imprint were measured by optical microscopy at 40× magnification. Hardness values (HV) were calculated via

$$HV = \frac{F}{A} = \frac{F}{((d^2) / (2 \cdot \sin(136^\circ/2)))} \approx 1.8544 \cdot \frac{F}{d^2} \approx 0.1891 \cdot \frac{F}{d^2}$$
, Where HV is the Vickers hardness number (kgf/mm²), F is the applied load in kilogram-force (kgf), and d is the average of the two indentation diagonals (mm).

Experimental Design and Characterization

Samples were divided into six groups (G1-G6) for a 30-day immersion test at 25±1°C, with measurements taken at 10, 20, and 30 days in both Control Groups (AA7025 alone) and Test Groups (AA7025-304L SS) configurations.

The experimental program comprised six groups (G1–G6) representing three corrosive environments and two coupling conditions. G1–G3 were used as control groups in which AA7025 was exposed without coupling to 304L stainless steel, whereas G4–G6 consisted of AA7025 coupled with 304L stainless-steel fasteners. Each group was evaluated at three exposure durations of 10, 20, and 30 days. For the uncoupled control groups (G1–G3), one specimen was assigned to each exposure duration, giving three specimens per group. For the galvanically coupled groups (G4–G6), two specimens were assigned to each exposure duration, giving six specimens per group. Thus, the experimental program comprised a total of 27 specimens. The experimental configurations used to investigate the corrosion behavior of AA7025 under different exposure environments and coupling conditions are illustrated in Fig.1. The six experimental groups (G1–G6) were configured according to the exposure medium and galvanic coupling condition.



Fig. 1. Experimental setup and specimen configurations for the six experimental groups (G1–G6)

The use of separate specimens at each exposure duration ensured that specimens could be removed at the designated exposure time without disturbing the remaining specimens. The coupled specimens were assembled using the same AA7025–304L stainless-steel configuration throughout the experiment to maintain consistent galvanic coupling conditions. The specimen identification, exposure environment, coupling condition, exposure duration, and number of specimens are summarized in Table 4.

Table 4. Experimental groups, coupling conditions, exposure environments, exposure durations, and number of specimens

Group	Environment	Coupling condition	10 days	20 days	30 days	Total
G1	Tap water	AA7025 alone	1	1	1	3
G2	3.5% NaCl	AA7025 alone	1	1	1	3
G3	1 M H ₂ SO ₄	AA7025 alone	1	1	1	3
G4	Tap water	AA7025 + 304L SS	2	2	2	6
G5	3.5% NaCl	AA7025 + 304L SS	2	2	2	6
G6	1 M H ₂ SO ₄	AA7025 + 304L SS	2	2	2	6
Total			9	9	9	27

Microstructural and compositional analyses were performed using optical Microscopy (**OM**), also called light microscopy, is used to examine the surface morphology and microstructure of a material using visible light and a system of optical lenses. Fourier transform infrared (FTIR) spectroscopy is a technique used to analyze materials by measuring how they absorb infrared light. SEM/EDS (Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy) used for investigating the surface morphology, microstructure, corrosion products, and elemental composition of metallic materials and their corrosion products. **X-ray Diffraction (XRD)** is used for identifying and characterizing the **crystalline phases, crystal structure, and corrosion products** present on a material surface.

Corrosion Rate and Mechanical Degradation Analysis

Corrosion rates were determined from mass-loss measurements following ASTM G31. Prior to immersion, the specimens were cleaned, dried, and weighed to obtain their initial masses. After the specified exposure period, the specimens were removed from the solution, cleaned to remove corrosion products, dried, and reweighed. The corrosion rate was calculated from the measured mass loss using $CR = (K \times W) / (A \times T \times D)$, where CR is the corrosion rate, K is the unit-conversion constant, W is the mass loss, A is the exposed surface area, T is the exposure time, and D is the material density. The calculated corrosion rates were subsequently converted to the reporting unit used in this study. Vickers microhardness measurements were performed before and after exposure using a 1 kgf load and a 10 s dwell time. Multiple indentations were made at representative locations on each specimen, and the average hardness was used to evaluate changes in surface microhardness following corrosion exposure.

Analytical and Numerical Corrosion Modeling

An analytical model based on mixed-potential theory and Tafel polarization relationships was developed to predict the corrosion potential (E_{corr}) and corrosion current density (i_{corr}) of the AA7025–SS304L galvanic couple. Numerical simulations were performed using COMSOL Multiphysics® 5.5. The three-dimensional geometry of the AA7025–SS304L assembly was developed in SolidWorks 2016 and subsequently imported into COMSOL Multiphysics as displayed in figure 2. The numerical model consisted of the AA7025 component, the SS304L pin/shaft, and the surrounding electrolyte domain.

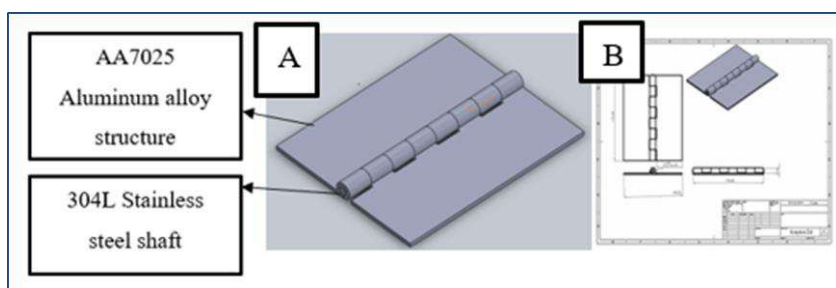


Fig.2. Geometric model of the AA7025-304L SS assembly used for COMSOL Multiphysics simulations

The calculated exposed surface areas of AA7025 and SS304L were 28,919.06 and 1,533.092 mm², respectively. The AA7025 surface was defined as the anodic electrode, whereas the

SS304L surface was defined as the cathodic electrode. The **Secondary Current Distribution** interface was employed to simulate the electrochemical behavior of the galvanic couple. Tafel kinetics were used to describe the electrode polarization behavior, while experimentally measured electrolyte conductivity values were incorporated to account for ohmic potential losses within the electrolyte. The resulting model was used to calculate the electrode potential and current-density distributions over the electrode surfaces.

Geometry Model Setup in COMSOL

The three-dimensional geometry of the AA7025–SS304L galvanic assembly was developed in SolidWorks 2016 and subsequently imported into COMSOL Multiphysics 5.5. The numerical model consisted of the AA7025 component, the SS304L pin/shaft, and the surrounding electrolyte domain. The calculated exposed surface areas of AA7025 and SS304L were 28,919.06 and 1,533.092 mm², respectively. The AA7025 surface was defined as the anodic electrode, whereas the SS304L surface was defined as the cathodic electrode.

The **Secondary Current Distribution** interface was employed to describe the electrochemical behavior of the galvanic couple. The electrode–electrolyte boundaries were assigned the corresponding electrode boundary conditions and polarization characteristics. The electrical conductivity of the electrolyte was specified according to the experimentally measured conductivity of each exposure solution. The resulting model accounted for both charge-transfer kinetics at the electrode surfaces and ohmic potential losses within the electrolyte.

Mesh Generation

The computational domain was discretized using a three-dimensional tetrahedral finite-element mesh. Local mesh refinement was applied near the electrode–electrolyte interfaces and other regions where relatively high spatial gradients in electric potential and current density were expected. Several mesh resolutions were evaluated to assess mesh sensitivity. The mesh adopted for the final simulations was selected based on the stability of the predicted electrode potentials and current-density distributions. This procedure reduced the possibility that the calculated corrosion parameters were significantly influenced by mesh resolution.

Study Parameters

The galvanic corrosion analysis considered the AA7025–SS304L couple in three electrolyte environments: tap water as displayed in table 5, 3.5 wt. % NaCl solution, and 1 M H₂SO₄ solution. The electrical conductivity values used in the numerical model were obtained directly

from the investigated solutions. The experimental exposure period was 720 h, corresponding to 30 days.

Table 5. Electrolyte properties and exposure conditions used in the numerical model

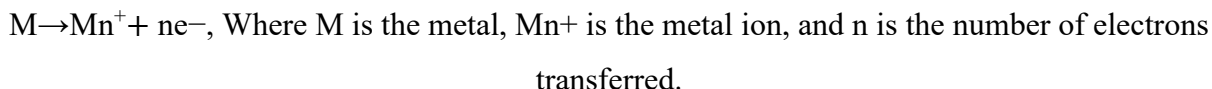
Electrolyte	Conductivity (S/m)	Immersion time
Tap water	0.22	720
3.5 wt.% NaCl	7.29	720
1 M H ₂ SO ₄	15.87	720

The anodic and cathodic Tafel slopes were 54.16 and 81.40 mV/dec for tap water, 123.00 and 124.71 mV/dec for 3.5 wt.% NaCl, and 164.40 and 759.54 mV/dec for 1 M H₂SO₄, respectively. The equilibrium potentials used for AA7025 and SS304L were −0.87 and −0.53 V, respectively. Because the AA7025 and SS304L surfaces have substantially different exposed areas, the analytical mixed-potential formulation was established using the total anodic and cathodic currents. The exposed AA7025 area was approximately 18.86 times larger than the exposed SS304L area; therefore, the electrode-area ratio was incorporated into the mixed-potential calculation.

Electrochemical Reactions at the Electrodes

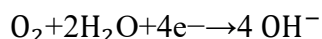
A galvanic couple consists of two dissimilar electrically connected metals exposed to a common electrolyte. Under the conditions investigated in this study, AA7025 acts predominantly as the anodic material and undergoes oxidation, whereas SS304L acts predominantly as the cathodic surface, where reduction reactions occur.

Anodic Reaction (Oxidation): The metal loses electrons:



Cathodic Reaction (Reduction): A species in the electrolyte gains electrons. Commonly, in acidic solutions: $2H^{+} + 2e^{-} \rightarrow H_2(g)$

or in neutral/alkaline solutions:



Electrode Potentials, Tafel Relationships, and Mixed-Potential Theory

The electrochemical behavior of each electrode reaction was described in terms of its equilibrium potential, (E_{eq}), and exchange current density, (i_0). The equilibrium potential

corresponds to the condition at which the anodic and cathodic partial reaction rates are equal and the net current is zero. The exchange current density represents the charge-transfer rate at equilibrium and provides a measure of the intrinsic electrochemical kinetics of the electrode reaction. For the analytical model, the anodic and cathodic polarization behavior was represented using Tafel relationships.

Numerical Simulation Corrosion Rate Calculation

The corrosion rate of AA7025 obtained from the COMSOL numerical simulation was calculated from the simulated corrosion current density using Faraday's law. The corrosion rate was determined from the anodic corrosion current density of the AA7025 surface according to

$$\text{Corrosion Rate (mm/yr.)} = \frac{K \cdot i_{\text{corr}} \cdot M}{n \cdot \rho}$$

Where for we use aluminum, $K = 3.27 \times 10^{-3}$ (mm·g/(A·cm·yr)), $M = 26.98$ g/mol (molar mass), $n = 3$ (electrons transferred), $\rho = 2.7$ g/cm³ (density), Faraday's **constant**: $F = 96485$ C/mol where(r_{corr}), is the corrosion rate, (i_{corr}) is the corrosion current density obtained from the COMSOL simulation, (M) is the molar mass of the dissolving metal, (n) is the number of electrons transferred during the anodic dissolution reaction, ρ is the density of AA7025, and (F) is Faraday's constant ((96,485C/mol)). The calculated corrosion rate was subsequently converted to the required unit of mm/year or mm/30 days for comparison with the experimental and analytical corrosion rates.

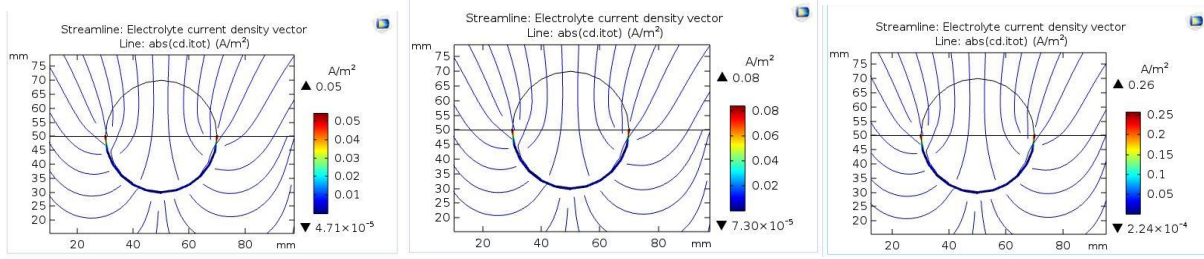
For the AA7025 alloy, the corrosion current density was obtained from the anodic electrode surface in the COMSOL Secondary Current Distribution model. The use of the anodic current density ensures that the calculated corrosion rate represents the material dissolution rate of AA7025, which acts as the anode in the AA7025–SS304L galvanic couple.

Corrosion Rate Analysis

Numerical result of corrosion rate

The COMSOL simulations successfully captured the corrosion behavior in both uncoupled (pitting) and coupled (galvanic) conditions. Figure 3 shows the simulated current density for the uncoupled AA7025 samples, representing baseline pitting corrosion driven by micro-galvanic cells at intermetallics. The simulation in (Fig.3) correctly predicts the hierarchy of environmental

aggressiveness, with the current density increasing from tap water (a) to NaCl (b) to H₂SO₄ (c), perfectly mirroring the experimental trend for groups G1, G2, and G3.



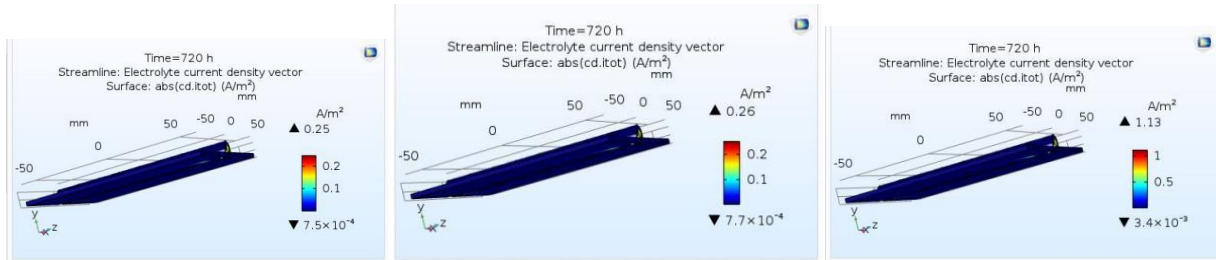
(a) in Tap Water,

(b) in 3.5% NaCl,

(c) in 1M H₂SO₄.

Fig.3. COMSOL simulation of electrolyte current density (A/m²) for uncoupled AA7025 (pitting corrosion) after 30 days

When the 304L SS fastener is introduced, the simulation shows a massive amplification of the corrosion current (Fig.4). Comparing the current density scales between Fig.3 and Fig 4, there is an order-of-magnitude increase, visually confirming the powerful accelerating effect of the macro-galvanic couple.



(a) Tap Water,

(b) 3.5% NaCl,

(c) 1M H₂SO₄.

Fig.4. COMSOL simulation of electrolyte current density (A/m²) for the galvanically coupled AA7025-304L SS system

Experimental result of corrosion rate

The corrosion rates of AA7025 were significantly influenced by both the environment and galvanic coupling. In non-galvanic conditions (G1-G3), the experimental corrosion rates were 0.0534 mmpy in tap water, 0.0864 mmpy in NaCl, and 0.2888 mmpy in H₂SO₄, showing that the acidic environment was the most aggressive. The introduction of galvanic coupling with 304L

SS (G4-G6) dramatically accelerated corrosion. The experimental corrosion rate surged to 0.2630 mmpy in tap water (a $4.92\times$ increase), 0.2690 mmpy in NaCl (a $3.16\times$ increase), and a catastrophic 1.1942 mmpy in H_2SO_4 (a $4.26\times$ increase).

Experimental, Analytical, and Numerical Corrosion Rate Comparison

The analytical, numerical, and experimental approaches exhibited consistent corrosion-rate trends across the six experimental groups, with the average values and standard deviations indicating close agreement among the three approaches. The corresponding results for G1–G6 are shown in Fig.5.

For the uncoupled AA7025 specimens, the average corrosion rate increased from G1 to G3. The average values were 4.458, 7.187, and 23.582 $\mu\text{m}/30$ days for G1, G2, and G3, respectively. The corrosion rate therefore increased from the tap-water environment (G1) to the 3.5 wt% NaCl environment (G2) and reached a substantially higher value in the 1 M H_2SO_4 environment (G3). The analytical, numerical, and experimental results followed the same general trend within these groups.

Galvanic coupling of AA7025 with 304L stainless steel increased the corrosion rate relative to the corresponding uncoupled conditions. The average corrosion rates were 21.953, 22.691, and 100.4 $\mu\text{m}/30$ days for G4, G5, and G6, respectively. Compared with G1, G2, and G3, the corresponding coupled conditions produced increases from 4.458 to 21.953 $\mu\text{m}/30$ days, from 7.187 to 22.691 $\mu\text{m}/30$ days, and from 23.582 to 100.4 $\mu\text{m}/30$ days, respectively. The greatest increase occurred under the acidic condition, where the AA7025–304L SS couple exhibited the highest corrosion rate.

The standard deviations among the three approaches were 0.049, 0.061, 0.424, 0.269, 0.421, and 1.672 $\mu\text{m}/30$ days for G1–G6, respectively. Although the standard deviation increased for G6, its magnitude remained small relative to the corresponding average corrosion rate of 100.4 $\mu\text{m}/30$ days. The relatively small deviations across the groups indicate close agreement among the analytical, numerical, and experimental results.

Overall, the analytical and numerical models reproduced the experimentally observed variation in corrosion rate for both uncoupled and galvanically coupled AA7025 specimens. The three approaches consistently identified the 1 M H_2SO_4 environment as the most aggressive condition and G6, corresponding to the AA7025–304L SS galvanic couple in the acidic environment, as

the condition with the highest corrosion rate as displayed in table 6. The average corrosion rate of G6 was approximately 100.4 $\mu\text{m}/30$ days, corresponding to approximately 1.22 mm/year.

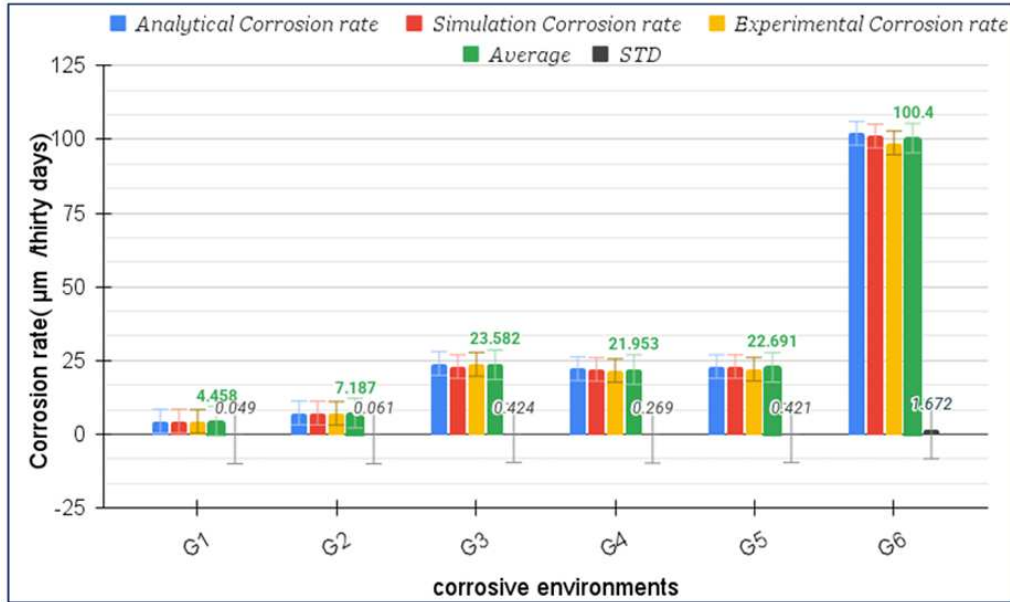


Fig.5. Comparison of analytical, numerical, and experimental corrosion rates for AA7025 alloy in six different corrosive environments after 30 days

Composition of Corrosion Products

XRD analysis in (Fig.6) identified the bulk corrosion products as calcite (CaCO_3) in tap water, bayerite ($\text{Al}(\text{OH})_3$) in NaCl , and aluminum sulfate hydrate ($\text{Al}_2(\text{SO}_4)_3$) in H_2SO_4 . FTIR spectroscopy (Fig.7) confirmed the chemical nature of these products through their characteristic absorption bands.

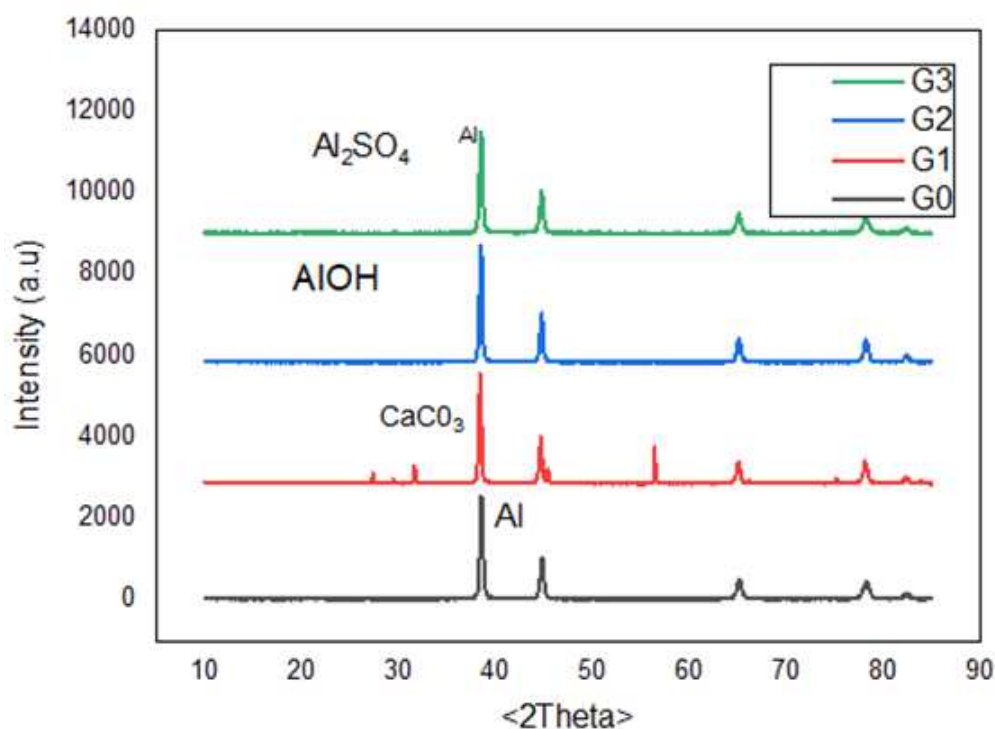


Fig.6. XRD patterns of corrosion products on AA7025 after 30 days. Key phases identified include calcite (G1), bayerite (G2), and aluminum sulfate hydrate (G3), compared to the uncorroded control (G0).of corrosion products on AA7025 after 30 days

The unexposed (G0) surface was clean, showing only faint native Al-O bonds below 900 cm^{-1} . Exposure to tap water (G1) resulted in water bands (~ 3400 , $\sim 1630\text{ cm}^{-1}$) and carbonate peaks (~ 1420 , $\sim 875\text{ cm}^{-1}$) from calcite. The 3.5% NaCl (G2) solution caused intense hydration signals (~ 3400 , $\sim 1630\text{ cm}^{-1}$), indicating hydrated aluminum oxides. Finally, 1M H_2SO_4 (G3) produced dominant sulfate bands (~ 1100 , $\sim 610\text{ cm}^{-1}$), confirming an aluminum sulfate product.

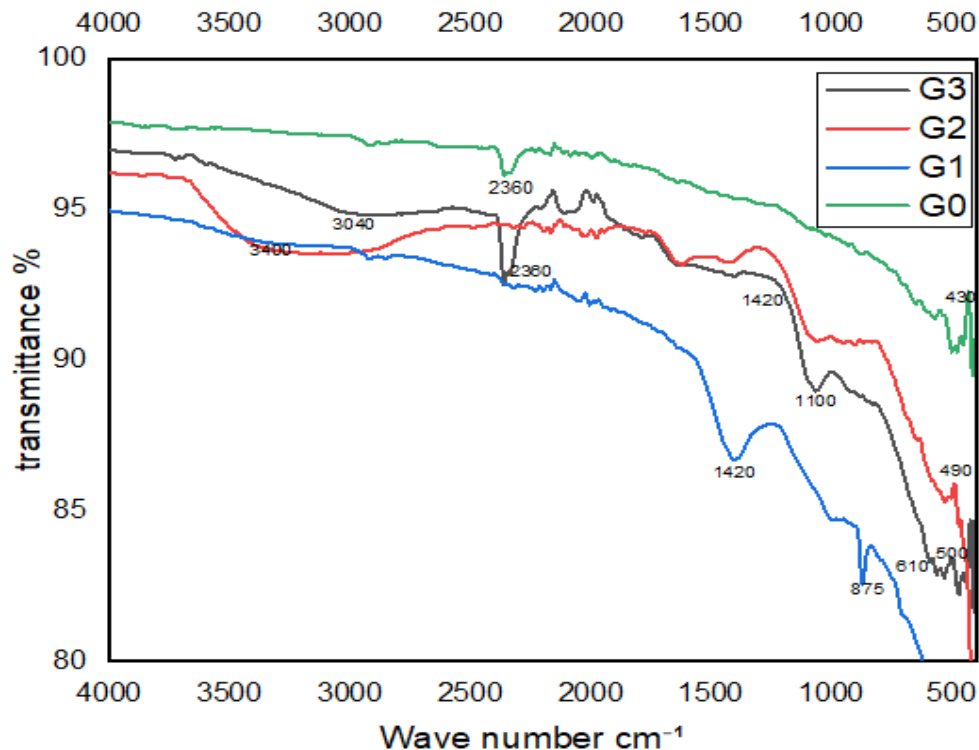


Fig.7. FTIR spectra of the AA7025 surface after 30 days

Microstructural Degradation and Hardness Loss

The degradation of the alloy's microstructure was visually confirmed by optical microscopy (Fig.8). The as-received sample (a) exhibited a smooth surface. In contrast, exposure to tap water (b) resulted in minor etching, exposure to 3.5% NaCl solution (c) caused localized pitting, and 1M H₂SO₄ solution (d) induced severe, widespread dissolution. This damage correlated directly with a loss in mechanical integrity, with Vickers hardness dropping from a baseline of 188.6 HV to as low as 167.9 HV (a 10.99% loss).

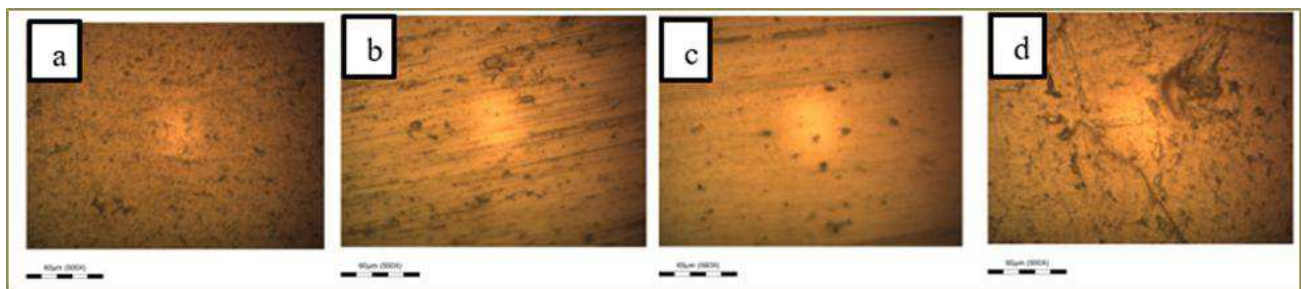
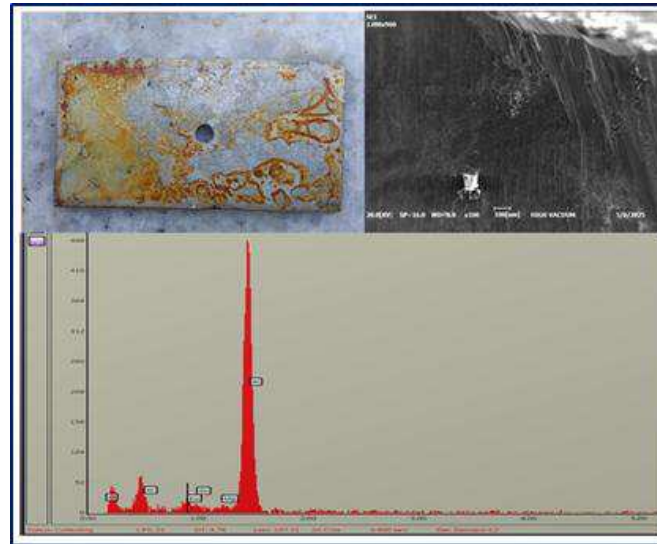
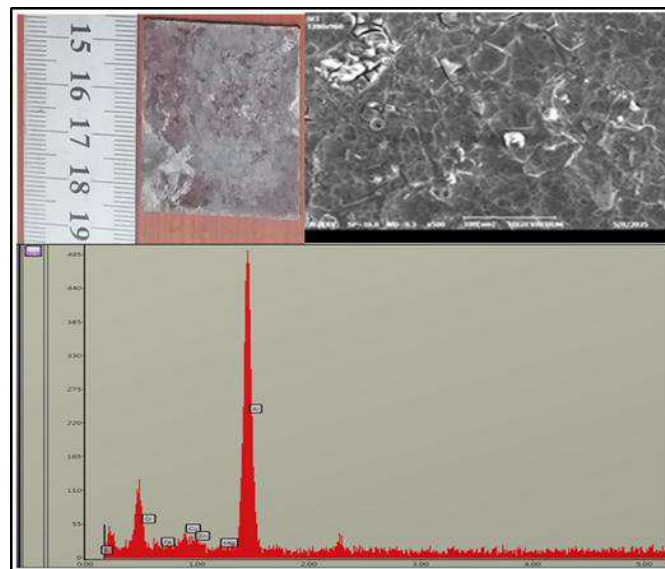


Fig.8. Optical microscopy images of the AA7025 alloy surface

The image shows, (a) as-received; (b) after 30 days in tap water; (c) after 30 days in 3.5% NaCl, showing distinct pits; and (d) after 30 days in 1M H₂SO₄, showing severe general corrosion. SEM analysis revealed distinct corrosion morphologies. In 3.5% NaCl (Fig.9), deep pits were observed to nucleate at the interface of the aluminum matrix and bright, cathodic intermetallic particles. In 1M H₂SO₄ (Fig.9), corrosion was widespread, resulting in a porous, degraded matrix with remnant, Fe-rich IMPs acting as local cathodes.



(a). AA7025 In 3.5% NaCl



(b) AA7025 In 1M H₂SO₄

Fig. 9. SEM microstructure and EDS analysis of AA7025 after corrosion exposure

In 3.5% NaCl, a pit forms directly adjacent to a cathodic intermetallic particle (IMP), with EDS confirming Cl attack. (b) In 1M H₂SO₄, the matrix is severely dissolved around remnant Fe-rich IMPs, with EDS confirming sulfur-based corrosion products.

Mechanical Degradation

The severe corrosion translated directly to a loss of mechanical integrity, evidenced by the progressive decline in Vickers hardness across all experimental groups, with a maximum loss of 10.99% in the G6 sample (Fig.10).

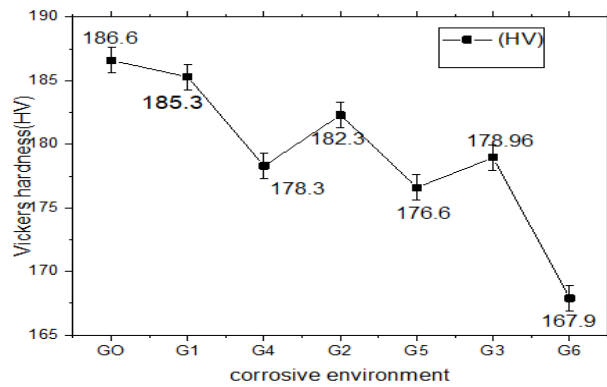


Fig.10. Vickers hardness of AA7025 samples after 30 days of exposure, illustrating the progressive loss of mechanical integrity

Table 6. Summary of corrosion rate, hardness, and hardness loss of AA7025 under uncoupled and coupled conditions after 30 days

Group	Condition	Corrosion rate (mmpy)	Hardness (HV)	Hardness loss (%)
G0	As-received	—	188.6	—
G1	Tap water	0.0534	185.5	1.63
G2	3.5 wt.% NaCl	0.0864	182.3	3.34
G3	1 M H ₂ SO ₄	0.2888	179.0	5.11

G4	Tap water + 304L SS	0.2630	178.3	5.47
G5	3.5 wt.% NaCl + 304L SS	0.2690	176.6	6.37
G6	1 M H ₂ SO ₄ + 304L SS	1.1942	167.9	10.99

Discussion

The results demonstrate that the corrosion behavior of AA7025 was governed by the combined effects of electrolyte chemistry and galvanic coupling with SS304L. For the uncoupled alloy, corrosion severity increased from tap water to 3.5 wt.% NaCl and was highest in 1 M H₂SO₄. The corrosion rates were 4.458, 7.187, and 23.582 $\mu\text{m}/30$ days for G1, G2, and G3, respectively. This trend was associated with differences in pH and electrolyte conductivity, together with changes in surface-film stability. The relatively low corrosion rate in tap water was accompanied by limited surface degradation and CaCO₃-containing deposits[8, 13]. In NaCl, chloride-containing species detected by EDS and localized attack observed by OM/SEM were consistent with chloride-induced destabilization of the protective aluminum oxide film. The highest corrosion rate in 1 M H₂SO₄ was associated with extensive surface degradation, sulfur-containing species, and aluminum sulfate identified by XRD, indicating enhanced active dissolution under strongly acidic conditions.

Galvanic coupling with SS304L substantially increased AA7025 corrosion in all three environments. The corrosion rate increased from 4.458 to 21.953 $\mu\text{m}/30$ days in tap water, from 7.187 to 22.691 $\mu\text{m}/30$ days in 3.5 wt.% NaCl, and from 23.582 to 100.4 $\mu\text{m}/30$ days in 1 M H₂SO₄, corresponding to increases of approximately 4.92, 3.16, and 4.26 times, respectively. These results demonstrate that SS304L acted as an effective cathodic surface, increasing the electrochemical demand for anodic dissolution of AA7025. The galvanic effect was therefore environment-dependent[14,15]. The relative increase was greatest where the uncoupled corrosion rate was initially low, whereas the acidic environment produced the highest absolute corrosion rate because the aggressive electrolyte already promoted rapid AA7025 dissolution.

The electrode-area ratio was also important in interpreting the galvanic response[16,18]. The exposed AA7025 area was 28,919.06 mm² compared with 1,533.092 mm² for SS304L, giving an area ratio of approximately 18.86:1. Accordingly, the mixed-potential condition was defined by equality of the total anodic and cathodic currents rather than equality of their current

densities[17]. This consideration was incorporated into the analytical mixed-potential model and provides a more physically representative description of the investigated galvanic configuration. The electrochemical degradation was accompanied by measurable changes in mechanical properties. The initial hardness of AA7025 was 188.6 HV and decreased to 185.53, 182.3, and 178.96 HV for G1, G2, and G3, respectively. Further degradation occurred after galvanic coupling, with G6 exhibiting the lowest hardness of 167.9 HV. The approximately 10.99% reduction in hardness for G6 indicates that severe corrosion was accompanied by deterioration of the near-surface mechanical condition. Although the relationship between corrosion and hardness degradation is well established, the quantitative correlation obtained here provides additional engineering information for the investigated AA7025–SS304L configuration.

The experimental results were consistent with the analytical mixed-potential calculations and COMSOL Secondary Current Distribution simulations. All three approaches reproduced the principal trend of increasing corrosion severity from tap water to NaCl and H₂SO₄ and the acceleration associated with galvanic coupling. The analytical model quantified the influence of electrode potentials, Tafel kinetics, exchange current densities, and electrode areas, whereas the COMSOL model provided the corresponding spatial distributions of potential and current density. The corrosion rate obtained from the simulated anodic current density was calculated using Faraday's law. This provided a direct connection between the numerical electrochemical response and material loss and supports the use of the numerical model for evaluating the corrosion behavior of the coupled assembly.

From an engineering perspective, the results demonstrate that the compatibility of AA7025 with SS304L fasteners cannot be assessed solely from the individual corrosion resistance of the two materials. Electrolyte chemistry, conductivity, electrode potential difference, exposed-area ratio, and cathodic kinetics collectively determine the severity of galvanic attack[19,20]. The 3.16–4.92-fold increase in corrosion rate observed after coupling provides a quantitative measure of the galvanic effect for the investigated configuration. In particular, the 100.4 $\mu\text{m}/30 \text{ day}$'s corrosion rate obtained for G6 indicates that additional corrosion-control measures are required for AA7025–SS304L assemblies exposed to strongly aggressive environments. Electrical isolation, protective coatings, optimized exposed-area ratios, or suitable cathodic-protection systems may therefore be required.

The additional COMSOL assessment of Al–0.1In, Zn, and Al–5Zn sacrificial anodes extends the numerical investigation from corrosion characterization toward corrosion-control evaluation. This provides a basis for comparing alternative protection configurations using the same electrochemical modeling framework.

The principal scientific contribution of the present study is therefore not the identification of a previously unknown corrosion mechanism for aluminum alloys, but the quantitative integration of environmental chemistry, galvanic coupling, electrode-area effects, electrochemical modeling, surface characterization, and mechanical degradation for the specific AA7025–SS304L configuration. By combining experimental observations with mixed-potential analysis and spatially resolved numerical simulation, the study establishes a quantitative framework for relating electrolyte conditions and galvanic interactions to corrosion rate and mechanical degradation. This integrated approach provides a basis for evaluating the corrosion performance and protection requirements of AA7025 structures incorporating SS304L fasteners under different corrosive environments.

Additionally, predictive models were successfully validated, showing excellent agreement between experimental corrosion rates and both analytical and numerical (COMSOL) simulations. All predictive errors were below 5% (0.07–4.44% for analytical-numerical; 1.71–3.86% for analytical-experimental), firmly establishing the reliability of the theoretical framework. Microstructural characterization further revealed specific degradation pathways significantly exacerbated under galvanic coupling: minimal surface alteration and CaCO_3 deposition in tap water; severe pitting corrosion with Cl detection and $\text{Al}(\text{OH})_3$ formation in 3.5% NaCl; and widespread general corrosion with S detection and $\text{Al}_2(\text{SO}_4)_3$ as the primary product in 1M H_2SO_4 . Future work should focus on the long-term experimental validation of the Al-5Zn sacrificial anode system to confirm its real-world effectiveness in preserving the structural integrity of AA7025 components in marine applications.

The corrosion of AA7025 is a multi-scale process initiated by micro-galvanic cells at intermetallic particles. These IMPs act as local cathodes, driving the dissolution of the surrounding aluminum matrix. The macro-galvanic couple with the 304L SS fastener acts as a powerful amplifier, dramatically increasing the rate of these IMP-driven processes. This is visually confirmed by the COMSOL simulations (Fig.3), which show a clear increase in galvanic current density that mirrors the measured corrosion rates. The specific chemical pathway is

dictated by the environment. The FTIR analysis (Fig.7) provides the chemical fingerprint for each pathway: carbonate scale formation in tap water, extensive hydration in NaCl, and sulfate product formation in H₂SO₄. The combined impact of all factors is summarized in the 3D corrosion map (Fig.11), which identifies the galvanically coupled, acidic condition as the most destructive. The COMSOL simulations provide a powerful tool for both predicting corrosion and designing protective systems. The high accuracy of the corrosion models, consistent with other simulation-based corrosion studies [12,21], validates their use for engineering design and lifetime assessment.

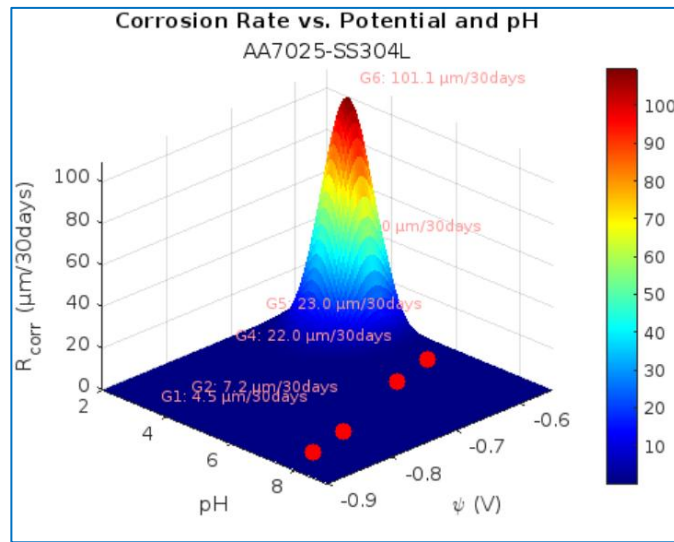


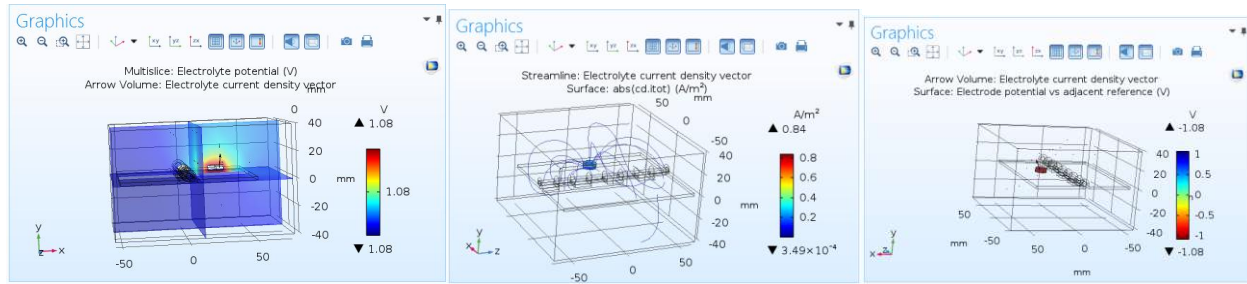
Fig. 11. 3D surface plot visualizing the relationship between corrosion rate, pH, and corrosion potential

COMSOL simulations were used to evaluate the performance of three sacrificial anodes for protecting the AA7025 alloy. The results (Table 7) showed that the Al-5Zn anode provided superior protection compared to pure Zn and Al-0.1In. The Al-5Zn anode generated the highest protective current density (0.84 A/m²) and induced the most negative polarization potential (-1.08 V) on the AA7025 surface. This potential is well below the typical protection threshold of -0.85 V, indicating a robust safety margin against corrosion.

Table 7. Comparative performance of simulated sacrificial anodes for AA7025 cathodic protection

Anode	Current Density(A/m ²)	Polarization(V)	Protection Uniformity
Al-5Zn	0.84	-1.08	Superior
Zn	0.71	-1.00	Good
Al-0.1In	0.64	-0.99	Moderate

To counteract the severe galvanic corrosion, a cathodic protection strategy using a sacrificial anode was simulated as shown in Fig.12. The protection mechanism relies on coupling the AA7025-304L SS assembly to a more active metal, which preferentially corrodes (acts as the anode), thereby protecting the AA7025 structure by forcing it to become a cathode. COMSOL simulations compared the performance of three anode materials. The results (Table 7) identified Al-5Zn as the optimal choice. Fig.12. illustrates its superior performance: the Al-5Zn anode generated a robust protective current density of 0.84 A/m² and uniformly polarized the entire AA7025 surface to a potential of -1.08 V. This is significantly more negative than the potentials achieved by Zn (-1.00 V) or Al-0.1In (-0.99 V) and provides a substantial safety margin below the -0.85 V protection threshold.



a) Electrolyte potential b) electrolyte current density c) electrode potential

Fig.12. COMSOL simulation of cathodic protection using an Al-5Zn anode

The results show (a) the electrolyte potential distribution and (b) the electrode surface potential, demonstrating uniform polarization of the AA7025 structure to a highly protective -1.08 V.

Conclusion

This research investigated the galvanic corrosion of AA7025 aluminum alloy coupled with 304L stainless steel fasteners across three environments (tap water, 3.5% NaCl, and 1M H₂SO₄). It combined experimental testing, numerical simulations (COMSOL, MATLAB), and advanced microstructural analysis (OM, SEM/EDS, FTIR). Predictive models showed high reliability, with experimental and numerical errors remaining below 5%. AA7025 baseline corrosion and mechanical loss scaled with environment severity: Future work will focus on long-term testing of an Al-5Zn sacrificial anode system to protect AA7025 in marine applications.

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Data Availability Statement

The datasets generated and/or analyzed during the current study are not publicly available due to internet reason but are available from the corresponding author on reasonable request.

Code availability Statement

The code generated and/or analyzed during the current study are not publicly available due to insert reason but are available from the corresponding author on reasonable request.

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project administration, M.W.T. All authors have read and agreed to the published version of the manuscript.

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