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Simulation Study of Galvanic Interaction in Alloy Metal Combinations in Acidic Environments

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ABSTRACT
Galvanic corrosion is a form of material degradation that occurs due to the electrochemical potential difference between two dissimilar metals in contact within an electrolytic environment. This study aims to simulate galvanic interactions between various alloy metal combinations under acidic conditions, with the objective of identifying the metal pairs most susceptible to corrosion and evaluating the resulting corrosion rates. The simulation was carried out using a numerical approach based on finite element method (FEM)-based software, which enables detailed visualization of galvanic current distribution and electrochemical potential mapping.

The simulation results indicate that metal combinations with greater electrochemical potential differences exhibit significantly higher corrosion rates, particularly affecting the metal acting as the anode. Furthermore, the acidity level (pH) of the environment was found to have a direct impact on the intensity of the corrosion process. This study provides a scientific foundation for safer material selection in structural design and mechanical systems operating in aggressive environments, and offers initial recommendations for mitigating galvanic corrosion.

KEY WORDS: *Galvanic corrosion, alloy metals, numerical simulation, acidic environment, electrochemical potential, corrosion rate, finite element method.*

NOMENCLATURE

pH	potential of hydrogen
mm	millimeters
g	gram
v	volt
mg/h	milligrams/hour

1.0 INTRODUCTION

1.1 Background
Corrosion is a process of metallic material degradation caused by electrochemical reactions between the metal and its surrounding environment. This process is one of the primary causes of damage to metal components across various industrial sectors, including construction, transportation, marine applications, and manufacturing. Among the different types of corrosion, galvanic corrosion is one of the most frequently encountered, particularly in systems that combine two or more metals with differing electrochemical potentials. In such conditions, the metal with the lower potential acts as the anode and corrodes at an accelerated rate, while the metal with the higher potential functions as the cathode and remains protected. This phenomenon can lead to premature material failure if not properly anticipated.

The application of alloy combinations in engineering systems is typically intended to optimize the performance of structural or mechanical components. For instance, steel is chosen for its strength, while aluminum is favored for its lightweight properties. However, when these dissimilar metals are integrated into a single system and exposed to an electrolyte-rich environment—such as seawater, chemical solutions, or acidic atmospheres—the risk of galvanic corrosion increases significantly. This poses a significant challenge in materials engineering, especially in selecting safe metal combinations, designing effective protection strategies, and implementing efficient prevention methods.

Acidic environments represent one of the most aggressive conditions that accelerate corrosion processes. Such environments may originate from industrial waste, acid rain, mining activities, or laboratory chemical processes. In these conditions, the high concentration of H^+ ions enhances the rate of electrochemical reactions and accelerates metal degradation, thereby increasing the risk of structural failure. It is therefore crucial to thoroughly understand how specific metal combinations interact in such environments and how corrosion rates can be minimized through proper material system design.

Although numerous experimental studies have been conducted to investigate galvanic corrosion, these methods are often time-consuming, costly, and involve complex procedural repetitions. Computational simulation approaches, on the other hand, offer a more efficient and flexible solution. Numerical

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methods such as the Finite Element Method (FEM) enable both visual and quantitative analysis of potential distribution, galvanic current flow, and corrosion intensity on the surfaces of contacting metals. With the aid of simulation software, the behavior of galvanic corrosion in various scenarios can be evaluated without the need to construct physical prototypes.

This study aims to simulate and analyze galvanic interactions among several combinations of alloy metals in an acidic environment. Through these simulations, it is expected to gain insights into how differences in electrochemical potential between metals influence corrosion rates and how acidic conditions accelerate degradation. The results of this research are intended to serve as a reference for engineers and researchers in selecting materials that are more resistant to galvanic corrosion, as well as a foundation for developing more effective mitigation methods, such as protective coatings, electrical isolation, and the use of sacrificial anodes.

By comprehensively understanding the characteristics of galvanic corrosion through simulation-based approaches, material system design processes across industries can be carried out in a safer, more economical, and sustainable manner.

1.2 Problem Statement

Galvanic corrosion is an electrochemical phenomenon that occurs when two dissimilar metals or metal alloys with different electrochemical potentials are in direct contact and immersed in an electrolyte environment, such as an acidic solution. Under these conditions, the metal with the lower potential becomes the anode and undergoes accelerated dissolution (corrosion), while the metal with the higher potential acts as the cathode and remains relatively protected. This phenomenon is commonly observed in various engineering structures and mechanical systems that utilize dissimilar metal combinations, such as in piping joints, marine constructions, vehicles, and chemical processing equipment.

The primary issue arising from this phenomenon is that improper selection of metal combinations—especially in aggressive environments such as acidic conditions—can significantly accelerate material degradation and drastically reduce the service life of components. Unfortunately, in practice, the aspect of galvanic corrosion is often underappreciated during the initial design phase of a system. Furthermore, experimental studies on galvanic corrosion are time-consuming, costly, and often face difficulties in maintaining consistent environmental conditions.

Therefore, a numerical simulation-based approach becomes an effective alternative for examining and predicting galvanic corrosion behavior more efficiently. Simulations allow for the visualization of potential distributions, galvanic current flow, and corrosion rates on metal surfaces under various material combinations and environmental conditions. However, there is still a gap in the literature concerning specific modeling of interactions between metal alloys in acidic environments, particularly in terms of metal pair variations and the influence of acidity levels on the intensity of galvanic corrosion.

Based on this background, several key research questions are formulated in this study:

1. What are the characteristics of galvanic interactions occurring between various alloy metal combinations in acidic electrolyte environments?
2. To what extent do electrochemical potential differences between metals affect the distribution of galvanic current and the corrosion rate on the anodic metal?
3. How does the acidity level of the environment (low pH) influence the rate and pattern of galvanic corrosion propagation?
4. Which metal combinations are most susceptible to galvanic corrosion in acidic environments, and what prevention strategies can be proposed based on the simulation results?

This study is expected to provide scientific contributions to the numerical understanding of galvanic corrosion mechanisms, and offer an efficient preliminary approach for designing material systems that are more resistant to corrosion in extreme environments.

1.3 Research Objectives

Galvanic corrosion is a highly complex electrochemical phenomenon that is often difficult to predict, especially when involving alloyed metals under extreme environmental conditions such as acidic solutions. A thorough understanding of the mechanisms behind galvanic corrosion and the influencing parameters is crucial to prevent component failure in various engineering systems. Therefore, this research is designed to contribute to the field through modeling and numerical analysis of galvanic interactions between alloyed metals in acidic environments, an area that has not been extensively studied using simulation-based approaches.

In general, the main objective of this study is to evaluate the behavior of galvanic corrosion in various combinations of alloyed metals within acidic environments using numerical simulations based on the finite element method (FEM). Through this approach, it is expected that a more accurate and visual understanding can be obtained regarding the distribution patterns of galvanic current, potential variation, and the prediction of corrosion rates between metals in direct contact within an electrolyte medium.

The specific objectives of this research are as follows:

1. To conduct modeling and numerical simulation of galvanic interactions between several commonly used alloy metal combinations in engineering, considering the electrochemical properties of each metal.
2. To analyze the distribution of galvanic current and the electrochemical potential profiles formed on the metal surfaces during the corrosion process, and to evaluate their impact on the dissolution rate of the anodic metal.
3. To identify the influence of environmental acidity (low pH values) on the intensity of galvanic corrosion occurring in the tested metal pairs, in order to understand the extent to which environmental conditions accelerate material degradation.
4. To determine the metal combinations with the highest risk of galvanic corrosion, based on quantitative simulation results and visualizations generated by numerical analysis software.
5. To develop initial recommendations for galvanic corrosion prevention strategies, whether through the selection of more electrochemically compatible metal pairs, the application of surface protective coatings, the use of intermetallic insulators, or other strategies applicable to the design of alloy-based

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engineering systems.

By achieving these objectives, the results of this study are expected to provide significant contributions to the field of materials science and corrosion engineering, as well as serve as an early reference for decision-making regarding material selection and corrosion protection in acidic working environments.

1.4 Research Benefits

This research is expected to provide both theoretical and practical benefits in the fields of materials engineering and corrosion control. Through a numerical simulation approach to galvanic interactions between alloyed metals in acidic environments, the results of this study can serve as a scientific foundation and technical reference for decision-making related to material selection and corrosion prevention efforts. More specifically, the expected benefits of this research are as follows:

1. Academically, the simulation results can enrich the literature in the field of materials engineering, particularly in understanding the mechanisms of galvanic corrosion in acidic environments.
2. Practically, the research findings can assist industries in selecting safer metal combinations for use in corrosive environments, as well as in designing more effective corrosion prevention strategies.
3. Time and cost efficiency, as numerical simulations allow for the analysis of corrosion behavior without the need for complex and expensive physical testing.
4. Risk control, by providing preliminary information on the potential occurrence of galvanic corrosion, thus aiding system designers in taking appropriate preventive measures.

Thus, this study not only contributes to the theoretical development of galvanic corrosion, but also offers practical technical solutions to support safer, more efficient, and sustainable engineering practices.

2.0 LITERATURE REVIEW

2.1 Fundamental Theory of Galvanic Corrosion

Galvanic corrosion is a type of electrochemical corrosion that occurs due to the interaction between two different metals that are electrically connected within an electrolytic environment. This phenomenon arises from the difference in electrochemical potential between the metals involved, which generates an electric current as a result of natural redox reactions on the metal surfaces. When two metals with differing electrochemical characteristics come into direct contact and are immersed in an ion-conducting medium, such as an acidic solution or seawater, a galvanic cell is formed. In this cell, the metal with a more negative electrochemical potential functions as the anode and undergoes oxidation (electron loss), while the metal with a more positive potential acts as the cathode and does not degrade—indeed, in some cases, it may even be protected from corrosion [1].

The anodic metal dissolves into the solution as metal ions, while a reduction reaction occurs at the surface of the cathodic metal, such as the reduction of hydrogen ions into hydrogen gas or the reduction of dissolved oxygen into hydroxide ions. The potential difference between the two metals is the primary driving force that causes electrical current to flow through the conductive medium. The greater the potential difference, the larger the galvanic current generated and the higher the corrosion rate of the anodic metal. Therefore, metal pairs that are far apart in the galvanic series or voltaic series tend to exhibit more severe galvanic corrosion compared to those with closer electrochemical potentials.

In addition to the potential difference, several other factors influence the severity of galvanic corrosion. One key factor is the surface area ratio between the anode and cathode. If the surface area of the anodic metal is significantly smaller than that of the cathodic metal, the corrosion current will be concentrated on a smaller area, greatly accelerating the corrosion rate. Other contributing factors include solution temperature, pH, salinity, and the presence of dissolved oxygen. For instance, in highly acidic environments, metals such as aluminum or zinc corrode more quickly because the passive layers that normally protect their surfaces can dissolve or break down.

To better understand and predict the behavior of galvanic corrosion, engineers and researchers often refer to the galvanic series, which ranks metals and alloys based on their electrochemical potentials in specific environments, such as seawater. Metals like magnesium, aluminum, and zinc are located on the anodic end of the series, whereas copper, silver, and platinum are on the cathodic end. Consequently, using extreme metal combinations in a single system without adequate insulation can result in rapid and uncontrolled material degradation.

A deep understanding of the fundamental theory of galvanic corrosion is crucial in engineering fields, particularly in the design of piping systems, marine structures, aircraft, vehicles, and chemical reactors. By understanding the mechanism, designers can avoid poor material selection and apply preventive measures such as the use of insulating coatings, physical separation of metals, or cathodic protection systems. In the research context, the study of galvanic corrosion also provides the foundation for developing numerical simulations and mathematical models to more accurately predict corrosion rates and patterns, thereby aiding in more informed and effective technical decision-making.

2.2 Characteristics of Alloy Metals and Their Electrochemical Potentials

Alloy metals are engineering materials composed of two or more metallic elements (and sometimes non-metallic elements) that are combined to enhance specific properties such as mechanical strength, wear resistance, or corrosion resistance. In the context of galvanic corrosion, it is crucial to understand that each metal or alloy has a distinct electrochemical potential, which reflects its tendency to undergo oxidation or reduction in an electrolytic environment.

The electrochemical potential of a metal is typically expressed in volts (V) relative to the Standard Hydrogen Electrode (SHE). Metals with more negative potentials tend to oxidize more readily and act as the anode in a galvanic cell, whereas metals with more positive potentials tend to function as the cathode. For example, magnesium has a potential of approximately -2.37 V versus SHE, making it highly reactive, while copper has a potential of around +0.34 V, indicating greater resistance to corrosion [2].

Several important alloy metals commonly used in

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engineering environments include:

1. Carbon steel: Offers good strength but is relatively susceptible to corrosion, especially in acidic or wet environments.
2. Aluminum and its alloys: Lightweight and protected by a natural passive oxide layer, but this layer can be compromised in acidic conditions, making it vulnerable to galvanic corrosion when paired with other metals.
3. Stainless steel: Contains chromium that forms a passive oxide layer, offering superior corrosion resistance. However, in acidic or chloride-rich environments, this passive behavior can deteriorate.
4. Copper and brass: Possess excellent electrical conductivity and decent corrosion resistance but can induce galvanic corrosion in more anodic metals like aluminum or steel.
5. Zinc: Commonly used as a sacrificial anode in cathodic protection systems due to its very low electrochemical potential, meaning it will corrode first to protect other metals.

Table 1. Alloy Metal Characteristics and Their Electrochemical Potentials

No	Type of Metal	Common Composition	Electrochemical Potential (V vs SHE)	General Characteristics
1	Aluminium (Al)	99.5% Al	-1.66	Lightweight, reactive, easily corroded
2	Carbon Steel (C-Steel)	Fe + C < 2%	-0.60 to -0.70	Strong,easily rusts in acidic environments
3	Stainless Steel 304	Fe, Cr (18%), Ni (8%)	-0.10	Corrosin resistant, passive layer formation
4	Copper (Cu)	99.9% Cu	+0.34	Good conducto, corrosion-resistant
5	Zinc (Zn)	99% Zn	-0.76	Highly active, common sacrificial anode

The galvanic series, which ranks metals based on their electrochemical potentials in a given environment (e.g., seawater), serves as a key reference for selecting metal combinations to avoid galvanic corrosion. The greater the distance between two metals in the galvanic series, the higher the risk of galvanic corrosion when these metals are electrically connected in a system.

By understanding the characteristics and electrochemical behavior of alloy metals, system designers can avoid material pairings that are prone to galvanic corrosion. This knowledge also provides a crucial foundation for numerical simulation processes, in which each metal is assigned an electrochemical potential value to predict current distribution and material degradation.

2.3 The Effect of Acidic Environments on Corrosion

Acidic environments are among the most aggressive conditions for metallic materials and metal alloys, particularly in the context of corrosion. In low-pH environments—such as those found in strong acid solutions (e.g., HCl, H_2SO_4, or HNO_3)—the corrosion rate typically increases significantly. This is due to the high concentration of hydrogen ions (H^+), which play a direct role in the electrochemical corrosion process, especially in the reduction reaction occurring on the metal surface. In galvanic corrosion systems, the abundance of H^+ ions accelerates the cathodic reduction process, thereby increasing the oxidation rate at the anode. In other words, acidic environments intensify the rate of galvanic corrosion by supporting the electrochemical reactions more aggressively.

Moreover, acidic environments can dissolve passive or protective layers that naturally form on the surfaces of some metals, such as aluminum, stainless steel, or titanium. These passive layers are typically stable metal oxides that prevent direct contact between the metal and corrosive solutions. However, under strong acidic conditions, these layers can degrade or dissolve, making the underlying metal more vulnerable to corrosion attacks—both general and galvanic. In galvanic metal pairings, even metals that are usually highly corrosion-resistant may suffer damage if their passive protection is lost due to acid exposure.

Another important influence of acidic environments on galvanic corrosion relates to solution conductivity. Acidic solutions generally have high electrical conductivity, which facilitates the movement of ions and accelerates the galvanic current flow between anode and cathode. This high conductivity allows corrosion systems to operate more efficiently, resulting in faster formation of corrosion current distribution and increased degradation rates at the anode. Additionally, strong acidity can affect the type of corrosion products formed, which in some cases may be more aggressive or promote structural damage [3].

From a practical perspective, understanding the influence of acidic environments is crucial in industrial applications such as chemical piping systems, chemical storage tanks, food processing systems, and mining facilities. In these environments, improper selection of metal materials or incompatible metal pairings can lead to rapid and hazardous galvanic corrosion. Therefore, research on corrosion in acidic environments is not only vital for advancing materials science but also plays a key role in improving the reliability and safety of engineering systems. By fully understanding how acidic conditions affect metal interactions, more accurate and efficient prevention strategies can be designed and implemented from the early stages of system planning.

3.0 RESEARCH METHODOLOGY

3.1 Materials and Test Specimens

The primary materials used in this study are several types of metal alloys commonly utilized in engineering and industrial

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construction, particularly those with differing potentials in the galvanic series. These metals were selected to identify possible galvanic interactions when used together in corrosive environments. The tested metals include:

1. Aluminum (Al) – A lightweight metal widely used in aircraft structures, vehicles, and household appliances. Aluminum is known for its passive properties; however, in acidic environments, its passive layer can dissolve, accelerating the corrosion rate.
2. Carbon steel (mild steel) – A metal extensively used in construction and manufacturing due to its strength and wide availability, but it is highly susceptible to corrosion.
3. Stainless steel (SS 304 or 316) – A corrosion-resistant metal containing chromium, with high resistance to corrosion. However, it can act as a cathode in galvanic pairs, thereby accelerating corrosion on the more anodic metal.
4. Copper (Cu) – A metal with high electrical conductivity and good corrosion resistance, but it often causes galvanic corrosion when combined with more reactive metals such as aluminum or steel.
5. Brass – An alloy of copper and zinc, commonly used in fittings and valves. It is relatively stable but exhibits interesting interactions when paired with ferrous metals or aluminum.

Each metal was cut into standardized test specimens with dimensions of approximately 20 mm × 20 mm × 2 mm, to facilitate comparison and calculation of corrosion rates among different metal pairs. The surfaces of the metals were polished using graded sandpaper (from coarse to fine grit), cleaned with ethanol or acetone, and dried to remove any contaminants, oils, or surface oxides that could influence the test results.

The electrolyte solution used was an acidic solution with a specific concentration, such as 1 M HCl, to represent a strongly acidic corrosive environment. The choice of acid type and concentration was intended to simulate extreme operational conditions that may accelerate galvanic corrosion.

The metal pairs were arranged in direct contact or electrically connected using conductive wires, and partially immersed in the solution for a specified period (24–72 hours), depending on the observation goals. During immersion, galvanic current measurements, mass changes, and visual documentation of corrosion products were conducted.

The selection of materials and test conditions aims to obtain representative data on actual galvanic corrosion behavior in engineering applications, while also providing valid input data for software-based numerical simulations.

3.2 Measurements and Observations

The measurements and observations in this study aim to obtain in-depth data regarding galvanic interactions between metal pairs in an acidic environment. One of the initial steps involves measuring the electrochemical potential of each metal using a three-electrode system, where the test metal serves as the working electrode, and the reference electrode used is either Ag/AgCl or a saturated calomel electrode. This measurement produces Open Circuit Potential (OCP) data, which indicates the tendency of a metal to act as an anode or cathode in a galvanic pair. Subsequently, the electrically connected metal pairs immersed in the acidic solution are tested to measure the galvanic current flowing between them. This measurement is performed using a multimeter or a sensitive current recorder, and is conducted periodically to assess the stability of the galvanic system and the intensity of the electrochemical reactions taking place.

In addition, the corrosion rate is calculated using the weight loss method, in which each metal specimen is weighed before and after the test, following the removal of corrosion products. The difference in mass is used to calculate the corrosion rate in units of mm/year, serving as an indicator of how rapidly the metal is degrading. To support the quantitative data, visual and microscopic observations of the metal surfaces are also conducted, both before and after testing. These observations aim to identify damage patterns such as uniform corrosion, pitting, or crevice corrosion. If available, the use of a Scanning Electron Microscope (SEM) can provide more detailed information about the surface structure after corrosion.

As part of the test condition controls, environmental parameters such as the pH and temperature of the solution are also measured regularly to ensure that the corrosive environment remains consistent throughout the testing period. With this comprehensive observational and measurement approach, the study is expected to provide an accurate depiction of galvanic corrosion behavior and serve as a reliable basis for validating the results of numerical simulations.

3.3 Data Analysis

The data analysis in this study was conducted systematically to interpret the results of measurements and observations related to the galvanic corrosion phenomenon in various alloy metal combinations under acidic conditions. The first step of the analysis involved processing the electrochemical potential and galvanic current measurement data between metal pairs. The potential difference between metals was analyzed to determine the direction of electron flow and the role of each metal as either an anode or a cathode. Periodically recorded galvanic current data was then used to evaluate the stability of the galvanic system and the intensity of the electrochemical interactions occurring during immersion. The larger the current generated, the stronger the galvanic interaction, and the faster the anodic metal experiences dissolution.

Next, the weight loss data was analyzed to calculate the corrosion rate of the metals in millimeters per year (mm/year), using standard formulas based on the weight loss method. These results were compared across different metal pairs to identify which combinations were most susceptible to corrosion. Additionally, the corrosion rates were compared with visual and microscopic surface observations to ensure that the physical degradation matched the numerical values obtained from the calculations. Corrosion patterns such as small pits or localized damage served as indicators of the dominant corrosion type.

The experimental data were then compared with the results of previously conducted numerical simulations. These simulations typically produced theoretical distributions of potential, current, and estimated corrosion rates. This comparison was used to validate the accuracy of the simulation models and assess how closely the experimental data aligned with or deviated from numerical predictions. Any discrepancies between empirical data and simulations were further analyzed to identify potential causes, such as surface imperfections, solution

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non-uniformity, or disturbances during the immersion process.

Finally, all processed data served as the basis for drawing conclusions regarding the influence of metal combinations and acidic environmental conditions on the rate and pattern of galvanic corrosion. The results of this analysis are expected to provide practical recommendations for material selection and corrosion prevention strategies in engineering systems operating in corrosive environments.

3.4 Evaluation and Validation

The evaluation and validation processes in this study were conducted to assess the accuracy and consistency between experimental results and numerical simulation outcomes related to the galvanic corrosion phenomenon. The evaluation began with a comparison of empirical data—such as electrochemical potentials, galvanic currents, and corrosion rates obtained from laboratory measurements—with the simulation outputs generated using numerical modeling software. The degree of agreement between the experimental trends and simulation predictions served as a key indicator of the simulation model's success in representing real-world systems. If the galvanic current values or corrosion distribution patterns for certain metal pairs showed significant discrepancies between the simulation and experimental results, further analysis was carried out to identify potential sources of deviation. These discrepancies could stem from assumptions within the model, such as irregular metal surfaces, local temperature variations, or imperfect solution mixing.

The validation process not only focused on numerical comparisons, but also on the alignment of observed physical phenomena, such as the shape and distribution of corrosion on metal surfaces documented through microscopy. If the simulation model was able to predict the spatial location or intensity of corrosion that corresponded with microscopic observations, the model's validity was considered high. Furthermore, sensitivity analyses were conducted on key simulation parameters—such as pH, temperature, or electrolyte conductivity—to determine how changes in conditions affected model outcomes. This approach helped test the robustness of the model under varying scenarios.

Overall, the purpose of the evaluation and validation process was to ensure that the research findings were not only numerically accurate but also reliable in representing the physical behavior of galvanic corrosion. A well-validated model allows simulation results to be used as predictive tools in designing more corrosion-resistant material systems, thereby enhancing the practical value of this research.

4.0 RESULTS AND DISCUSSION

4.1 Electrochemical Potential Differences

The difference in electrochemical potential between metals is a key factor that determines the occurrence of galvanic corrosion in systems consisting of two dissimilar metals connected in an electrolytic environment, such as an acidic solution. Each metal has a standard electrode potential that reflects its tendency to undergo oxidation or reduction. In this context, metals with more negative potentials tend to act as anodes, meaning they undergo oxidation and dissolve into the solution as ions, while metals with more positive potentials become cathodes and are more protected from corrosion.

In this study, open circuit potential (OCP) measurements showed that aluminum and carbon steel have lower electrochemical potentials compared to copper and stainless steel. Therefore, when aluminum is coupled with copper, or carbon steel with stainless steel, aluminum and carbon steel will act as anodes and will corrode at a higher rate. This phenomenon aligns with the principles of the galvanic series, where a greater potential difference between two metals results in a stronger driving force for the galvanic reaction and a higher risk of corrosion on the anodic metal.

Understanding these potential differences is a crucial foundation for material selection to prevent premature material degradation due to galvanic interaction, especially in engineering systems operating in corrosive environments such as in the chemical industry, marine applications, and laboratory equipment.

4.2 Galvanic Current Measurement

The galvanic current generated between two dissimilar metals in an acidic environment serves as an important indicator for assessing the rate of electrochemical reactions and the overall stability of the galvanic system. In this study, galvanic current measurements were performed by connecting test metals through an external circuit and immersing them in an HCl solution as the electrolyte. The measurement results showed that the initial current generated tended to be high during the first few minutes of immersion, especially for metal pairs with a large electrochemical potential difference, such as aluminum–copper and carbon steel–copper. This high current indicates a rapid oxidation rate at the anode metal due to electron transfer to the cathodic metal.

However, over time, the galvanic current tends to decrease and stabilize. This reduction is generally attributed to the formation of corrosion product layers on the anode surface, which can slow down the release of metal ions into the solution and hinder direct contact between the metal and the electrolyte. The stability of the galvanic system is strongly influenced by factors such as metal composition, solution pH, temperature, and immersion duration.

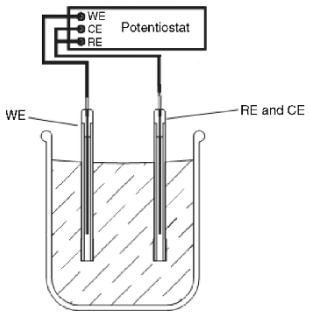

Figure 1. Schematic Setup Diagram for Galvanic Current Measurement

Systems that produce low and relatively stable galvanic currents, such as stainless steel–copper pairs, indicate that both metals have better corrosion resistance and exhibit minimal galvanic interaction. Thus, observing galvanic current values not only provides insights into the intensity of corrosion but also helps evaluate the performance of metal combinations over time,

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as well as the potential for cathodic protection or material failure that may occur in corrosive environments [4].

4.3 Corrosion Rate Based on Mass Loss

The corrosion rate based on mass loss is a classical yet highly effective method for measuring how rapidly a metal degrades when exposed to a corrosive environment—in this case, an acidic solution. In this study, the corrosion rate was determined by weighing the metal specimen before and after immersion for a specified period, typically measured in hours or days. The difference in mass reflects the amount of metal material that has dissolved into the solution due to the corrosion reaction. The corrosion rate is then calculated in units of millimeters per year (mm/year) using a standard formula based on mass loss, specimen surface area, immersion time, and metal density [5].

Test results showed that metals acting as anodes in galvanic couples, such as aluminum and carbon steel, experienced significant mass loss compared to metals acting as cathodes, such as copper and stainless steel. For instance, the aluminum–copper pair exhibited the highest corrosion rate due to the large potential difference and the high reactivity of aluminum in an acidic environment. Conversely, the stainless steel–copper pair showed minimal mass loss, indicating better corrosion resistance.

Table 1. Example of Corrosion Rate Based on Mass Loss

No	Metal	Δm (g)	Time (hours)	Corrosion Rate (mg/hour)
1	Aluminum	0.400	24	16.67
2	Steel	0.300	24	12.50
3	Copper	0.020	24	0.83

This method not only provides a quantitative assessment of the extent of metal degradation but also helps validate galvanic current measurements and numerical simulations conducted earlier. The correlation between mass loss data and visual/microscopic surface observations strengthens the understanding of the underlying corrosion mechanisms, both general and localized. Therefore, the results of this study can serve as a reference for selecting materials that are more resistant to corrosive attacks in industrial environments [6].

4.4 Visual and Microscopic Surface Observation

Visual and microscopic surface observations were conducted to directly identify the form, pattern, and extent of damage caused by galvanic corrosion on metal specimens after immersion in an acidic environment. After testing was completed, the metal specimens were cleaned of corrosion products using a standard cleaning solution, then observed macroscopically to examine color changes, stains, and visible surface damage. Subsequently, the metal surfaces were examined using an optical microscope or an electron microscope (if available) to observe surface morphology in greater detail [7].

The observations showed that metals acting as anodes experienced significantly more severe damage compared to cathodic metals. For example, in the aluminum–copper pair, the aluminum surface exhibited small pits (pitting corrosion), delamination of the outer layer, and a rough, uneven appearance. This indicates that the corrosion occurred in a localized and aggressive manner at specific points rather than uniformly. Conversely, the copper surface remained relatively clean, shiny, and showed no significant damage due to its role as the cathode in the galvanic system.

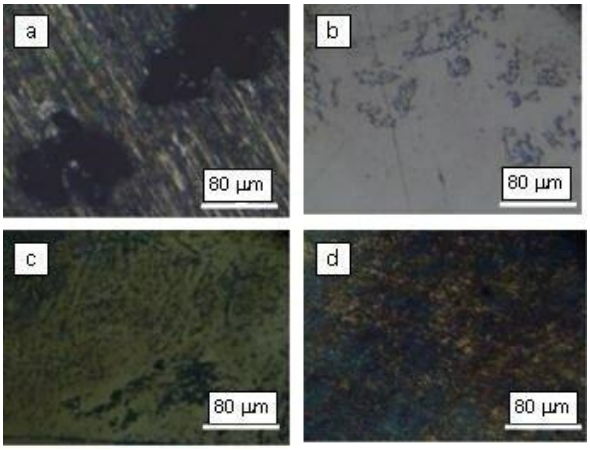

Figure 2. Microscopic observation of the samples surface after corrosion tests in 0.9 % NaCl solution a). un-implanted substrate, b). implantation time of 20 min., c). implantation of 30 min., d). implantation time of 40 min.

The corrosion patterns observed microscopically also supported the mass loss data and galvanic current values, where specimens with the highest corrosion rates showed the most severe surface damage. Microscopic observation provides important visual evidence in understanding the corrosion mechanisms at play and serves as a verification tool for electrochemical measurements and numerical simulations previously conducted [8].

Thus, the combination of visual and microscopic observations becomes a crucial step in evaluating the corrosion resistance of metals in a galvanic system and in designing effective corrosion protection strategies.

4.5 The Influence of Acid Concentration and pH

The concentration and pH of the acidic solution have a highly significant impact on the rate and mechanism of galvanic corrosion occurring between dissimilar metal pairs. In this study, HCl solution with varying concentrations was used to evaluate how the level of acidity affects the intensity of electrochemical reactions between metals. The test results showed that the higher the concentration of HCl (the lower the pH of the solution), the greater the galvanic current generated between the anode and cathode metals. This indicates that a more acidic environment increases the activity of hydrogen ions in the solution, which act as electron acceptors at the cathode. Consequently, the reduction reaction is accelerated, which in turn speeds up the oxidation process at the anode metal [9].

Moreover, environments with very low pH tend to inhibit the formation of protective passivation layers on certain metals, such as aluminum or carbon steel, thus increasing their susceptibility to localized corrosion such as pitting or crevice corrosion. On the other hand, in solutions with higher pH (lower acid concentration), the corrosion rate tends to be slower and the

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surface of the anodic metal remains more stable.

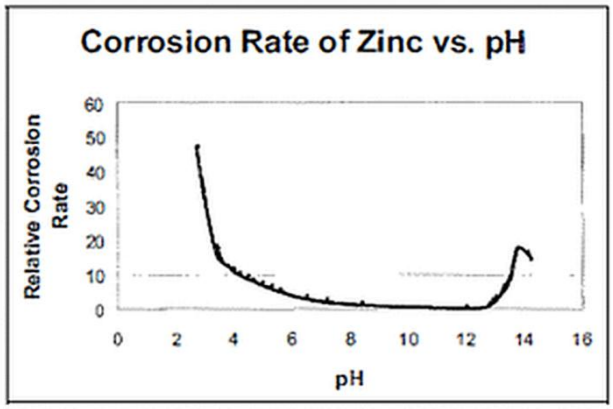

Figure 3. Corrosion Rate of Zinc against pH

Mass loss data and microscopic observations support these findings, as more severe surface damage was observed on anode metals in highly acidic environments. Understanding the influence of concentration and pH is crucial, especially in industrial applications involving the use of metals in aggressive chemical environments. This knowledge can be used as a basis for adjusting operating conditions, selecting protective materials, or adding corrosion inhibitors to extend the service life of the materials used [10].

5.0 CONCLUSION AND SUGGESTIONS

5.1 Conclusion

Based on the results of simulations and experimental testing, it can be concluded that galvanic corrosion is strongly influenced by the electrochemical potential difference between metals, the acidic environment characteristics, and the physicochemical properties of the materials used. Metal combinations with large potential differences—such as aluminum-copper and carbon steel-copper—exhibited higher corrosion rates, with the metal possessing a more negative potential acting as the anode and undergoing significant material degradation. Acidic environments with low pH were proven to accelerate corrosion rates, inhibit the formation of passivation layers, and increase the aggressiveness of electrochemical reactions.

The numerical simulations successfully mapped the distribution of galvanic current and potential in alignment with the damage patterns observed through visual and microscopic inspection. Therefore, selecting appropriate metal combinations and controlling environmental conditions are essential strategies for mitigating galvanic corrosion, especially in engineering applications within corrosive environments. This research is expected to serve as a reference for designing more durable and efficient material systems for use in acidic conditions.

5.2 Suggestions

Based on the results of the study and analysis of galvanic interactions between alloyed metals in acidic environments, several key steps can be used as references in engineering practices and future research. The prevention of galvanic corrosion does not solely depend on material selection but is also greatly influenced by system design, environmental conditions, and the implementation of protective measures. The following recommendations are derived from this study:

1. The use of metal pairs with small electrochemical potential differences is highly recommended to reduce the rate of galvanic corrosion. Electochemically compatible metal combinations tend to result in more stable systems over the long term.
2. In situations where using metals with significant potential differences is unavoidable, additional protective measures such as protective coatings, insulation between dissimilar metals, or the use of sacrificial anodes should be applied to protect the main structural metal from damage.
3. Maintaining a stable and not excessively low pH is essential to slow down corrosion rates. The use of corrosion inhibitors is also recommended to suppress electrochemical reactions, particularly in aggressive acidic environments.
4. Further studies should include testing in real-world operational environments to obtain more applicable and representative results that reflect actual field conditions.
5. Improvements to simulation models are necessary, including the incorporation of variables such as temperature, fluid flow rate, and exposure time, to make predictions of galvanic corrosion behavior more comprehensive and reflective of real conditions.

By implementing these measures, the potential damage caused by galvanic corrosion can be minimized, and the durability of materials used in corrosive industrial systems can be significantly improved. Furthermore, these recommendations serve as an initial foundation for developing more effective and sustainable corrosion protection strategies.

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