Studying Corrosion on Various Metals in a Simulated Biological Setting

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I. Introduction

Corrosion is a chemical process that leads to the deterioration of metals as they interact with their environment, which can compromise structural integrity in industrial and biomedical applications. This experiment will aim to analyze the oxidation of various metals in a simulated biological environment to understand how coatings and galvanic interactions influence corrosion. Iron nails (both plain and zinc coated) will be placed in a gelatinous material that mimics bodily conditions, allowing for observation of oxidation reactions over time. Additionally, a galvanic series will be constructed by measuring voltages across metals submerged in a salt solution to assess their relative reactivity and corrosion potentials. These findings will provide insight into corrosion mechanisms relevant to biomedical materials and structural applications. By evaluating different metals under controlled conditions, this study will help determine effective strategies for corrosion prevention in real-world settings.

II. Background

The degradation of metals due to interactions with environmental elements such as oxygen, water, and salts is a significant concern in various industries, including biomedical engineering. A common example is iron oxidation, where iron reacts with oxygen and water to form iron (III) oxide, or rust. However, not all metals corrode in the same way. Some, like aluminum and titanium, develop a passive oxide layer that prevents further oxidation, enhancing their corrosion resistance. Another factor of corrosion is the formation of galvanic cells, which occur when two different metals are electrically connected in an electrolyte. In a galvanic cell, the more reactive metal (anode) donates electrons and corrodes more rapidly, while the less reactive metal (cathode) remains protected. This process creates a voltage potential between the two metals, which can be measured to determine their relative reactivity. The anode in this interaction is referred to as a sacrificial anode, as it sacrifices itself to protect the cathode structural stability. A similar concept will be seen with the iron nail wrapped in copper wire. Understanding galvanic interactions is critical in designing materials that resist corrosion in harsh environments. This experiment will analyze both general corrosion in a body-like environment and the voltage potential across different metals in a galvanic cell. (Reference 1)

In biomedical applications, corrosion resistance is crucial, as metallic implants are exposed to the body's electrolytic environment. Titanium and its alloys are widely used in medical implants due to their ability to form a stable passive oxide layer, reducing corrosion and improving biocompatibility. However, when different metals are combined in an implant or medical device, galvanic corrosion can occur, accelerating material degradation and potentially causing dangerous biological effects. Understanding these corrosion mechanisms helps engineers design safer, longer-lasting biomedical devices that minimize material breakdown and ion release in the body. Builders also have to consider corrosion resistance as their structures need to be sound for long durations of time. Corrosion can cause structural flaws, which could be detrimental for public safety. (Reference 2)

III. Experiment Procedure/Materials/Methods

For the first part of the experiment, 9 plain straight steel nails, 3 zinc-coated (galvanized) nails, and 1 titanium surgical screw were collected and washed in a tri-pour beaker. Six labelled petri dishes would contain two nails each: 3x dishes containing steel vs. galvanized nails (A) and 3x dishes containing steel vs. steel nails with half wrapped with copper wire (B) (as demonstrated in Appendix A). The titanium screw was placed into one of the B samples. In a separate glass beaker with a hot plate and stir bar, 360 ml water was mixed with 2.4 g NaCl and 2 grounded tablets of $Mg(C_7H_5O_3)_2$. In another beaker, 6 packets containing 7 grams of gelatin were mixed with 90mL water and placed into the hot solution. Once the mixture was properly dissolved, it was poured over each petri dish sample to cover the nails completely. The petri dishes were placed into a fridge for 30 minutes to solidify. Observations and pictures of the petri dishes were recorded for intervals approximating 1, 2, 3, 4, 5, 6, 12 and 24 hours, 3 days, and 7 days following this period.

For the second part of the experiment, we began by stirring a solution containing 3% sodium chloride. We then used the provided metal samples of zinc, nickel, aluminum, and copper to behave as anodes or cathodes. Only zinc and copper were used as anodes (but also used as cathodes), which were individually tested with all other metals acting as cathodes. The anode and cathode were connected to a multimeter's negative and positive terminals, respectively. Both metals were submerged at the same time into the solution, with the terminal connections above the solution (as demonstrated in Appendix B). First, a zinc anode was tested against the three other metals. Then, copper was used as an anode and tested against the three other metals. Voltage measurements were recorded for each applicable combination of anode and cathode after a consistent amount of submersion time.

To reiterate, materials involved in experiment 1 include steel nails, zinc coated (galvanized) nails, steel with copper wire nails, and a titanium screw. Materials involved in experiment 2 include thin strips of zinc, nickel, aluminum, and copper.

IV. Results

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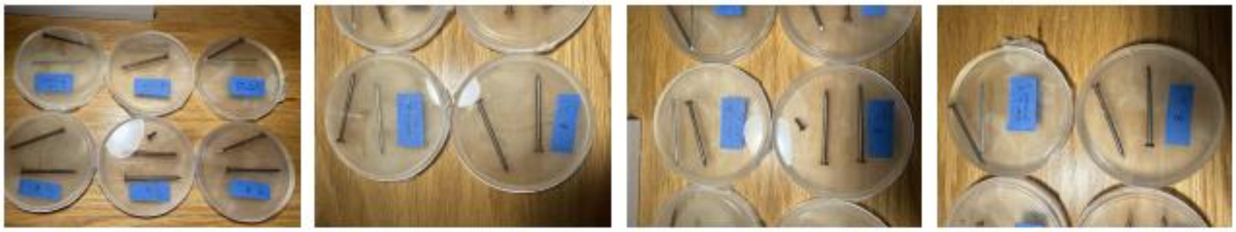
4:24PM (2/12/25):



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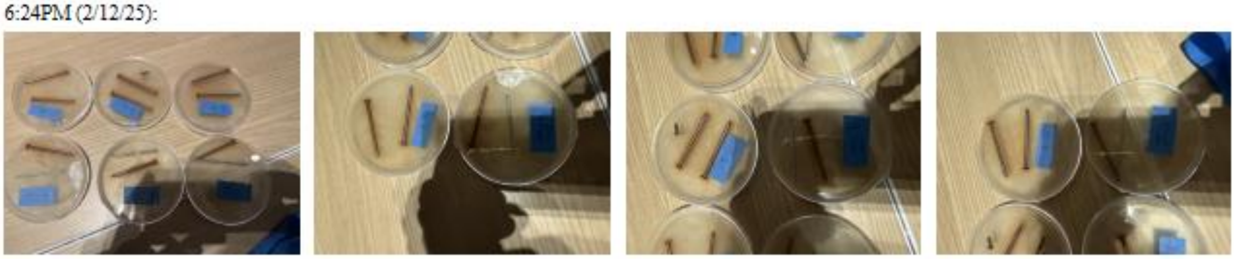

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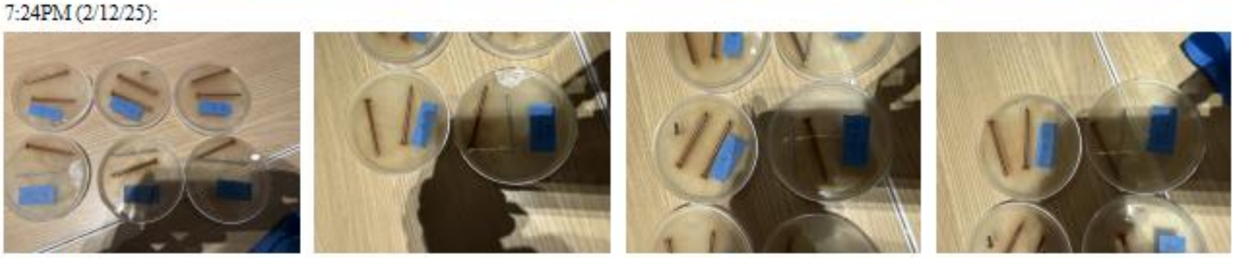

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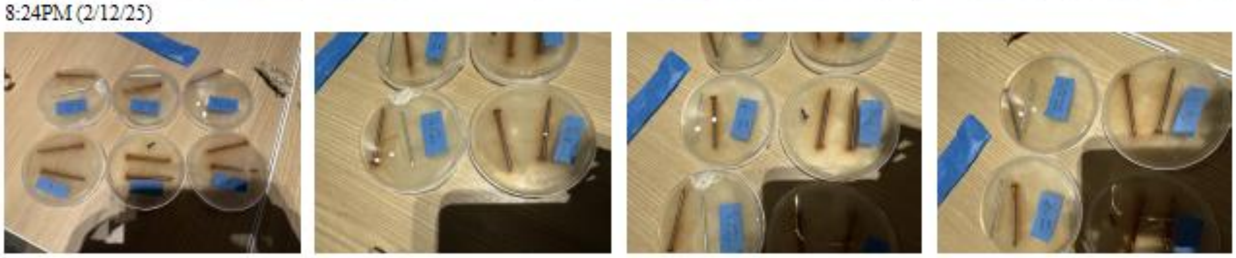


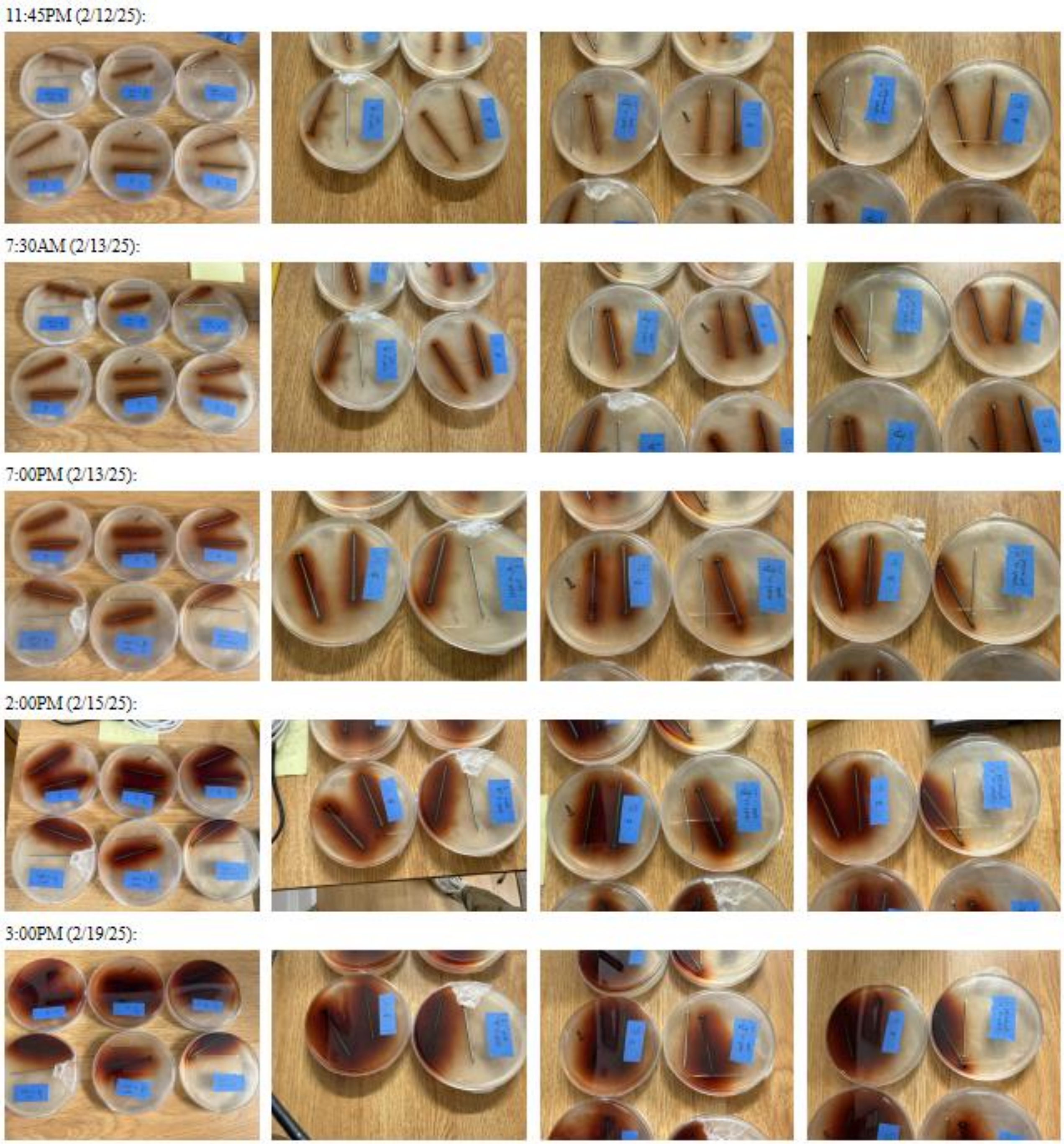


Figure 1: Series of images showing progression of corrosion for all petri dishes and their respective time intervals

Note: Start time of this experiment was 2:24 PM on 2/12/25

As seen in Figure 1, the nails showed definite signs of corrosion as time passed. However, not all the nails corroded in the same manner. The galvanic steel nails and the titanium screw showed almost no signs of corrosion. The brown seen in the images above are the result of the nails being too close together, so the corrosion from the steel nail surrounded the galvanized nail. When comparing the regular steel nail and the steel nail wrapped in copper wire, it seems that the latter showed more corrosion than the former. As seen in Figure 1, corrosion started roughly 3 hours after the experiment. The most notable progression was between the third and seventh day, which was the largest time interval between photographs.

Zinc As Cathode	
Anode	**Voltage (mV)**
Nickel	231
Aluminum	51
Copper	741

Table 1: Voltages for different anode materials when zinc is acting as the cathode

Copper As Cathode	
Anode	**Voltage (mV)**
Nickel	-352
Aluminum	-536
Zinc	-643

Table 2: Voltages for different anode materials when copper is acting as the cathode

As seen in table 1, copper was the most reactive anode when zinc was the cathode, with a voltage of 741 mV, followed by nickel with 231 mV and aluminum at 51 mV. A notable difference between Table 1 and Table 2, was that Table 2 showed all negative values for voltage, while Table 1 showed all positive voltages. When copper was the cathode, zinc was the most reactive with a voltage of -643 mV, followed by aluminum with -536 mV, then zinc with -352 mV. Interestingly, when zinc and copper swapped places (cathode/anode), the voltage when copper was the cathode was less intense than when copper was the cathode.

V. Discussion

The results of this experiment highlight key corrosion behaviors that engineers must consider when selecting materials for real world applications. The plain steel nails, as expected, exhibited significant corrosion over the time span of the experiment while in the gelatin–based environment. This corrosion was a result of oxidation when exposed to the moisture in the gel. The zinc-coated (galvanized) nails exhibited much less corrosion; this lack of corrosion is due to the zinc acting as a sacrificial node and protecting the internal steel from moisture. The copper wrapped steel nails corroded the nails more rapidly compared to the standard steel nails, following the effects of galvanic corrosion. In this test case the copper is less reactive than steel which in turn speeds up the oxidation of the steel as steel becomes the sacrificial node. The titanium screw remained basically unaffected, showcasing why titanium is often used in the biomedical field for implants due to its passive corrosion resistance.

The galvanic cell experiments further validated these trends. Copper produced the highest voltage when acting as an anode against zinc with a reading of 741mV. When copper was used as the cathode the voltage readings were negative, meaning the other metals were more reactive and oxidized. Zinc showed the highest negative voltage of –643 mV, exhibiting its strong tendency to donate electrons and corrode in favor of protecting a more noble metal. The results from this experiment show how the electronegativity of metal and their differences can change corrosion rates.

From an engineering perspective these results emphasize the importance of choosing the right materials for applications particularly in the biomedical field. For instance, materials like titanium are corrosion resistant, thus they won't degrade and wone release unwanted material into the body. Whereas materials like iron, even if galvanized, would still corrode and release unwanted metal ions into the body. Furthermore, knowledge of corrosion is helpful when designing for environments where a device or machine may be exposed to fluids or humidity. Further testing would include long-term durability of materials such as titanium and different titanium alloys in similar or more challenging conditions.

VI. Conclusions

This experiment was conducted in two parts to assess both direct corrosion and galvanic interactions among different metals in simulated environments. In the first phase, steel nails, galvanized nails, copper-wrapped steel nails (demonstrated in Appendix A), and a titanium screw were immersed in gelatinous medium prepared by dissolving gelatin in a salt solution enhanced with magnesium acetate. Observations revealed that while plain steel nails exhibited significant oxidation, the galvanized nails suffered much less corrosion due to the protective action of the zinc coating acting as a sacrificial layer. In contrast, the copper-wrapped steel nails experienced accelerated corrosion, highlighting the detrimental effects of galvanic interactions, whereas the titanium screw showed minimal corrosion, demonstrating its superior resistance in such environments.

In the second phase, a series of galvanic experiments were conducted using metal strips of zinc, nickel, aluminum, and copper submerged in a 3% sodium chloride solution. By pairing different metals as anodes and cathodes, voltage measurements were recorded to assess their relative reactivity (as demonstrated in Appendix B). Notably, copper produced the highest voltage when functioning as an anode against zinc, while negative voltage readings when copper acted as the cathode underscored the enhanced corrosion tendency of its counterparts in a galvanic pair. These findings affirm that differences in metal reactivity and electronegativity are key determinants of corrosive behavior. The experiment elucidated the corrosion mechanisms in simulated biological and saline environments. Additionally, it underscored the necessity to employ the proper materials and protective strategies in real world applications.

VII. References

Reference 1:

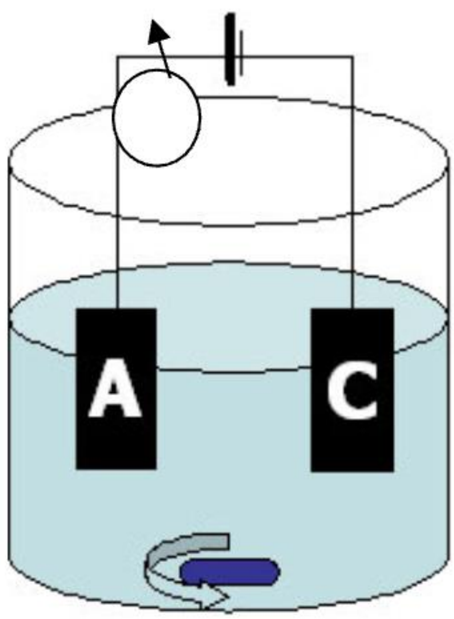
IEM Canada. *Fundamentals of Corrosion: Mechanisms, Causes, and Preventative Methods.*https://iem.ca/pdf/resources/Fundamentals%20of%20Corrosion_%20Mechanisms%2C%20Causes%2C%20and%20%20Preventative%20Methods.pdf. Accessed 24 Feb. 2025.

Reference 2:

The Electrochemical Society. *Galvanic Corrosion in Biomedical Applications.* https://www.electrochem.org/dl/interface/sum/sum08/su08_p31-34.pdf. Accessed 24 Feb. 2025.

VIII. Appendix

Appendix A – Steel nail half wrapped in copper wire



Appendix B - Setup for measuring potential