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Results of a Simple Corrosion Experiment in a Freshman Materials Course

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Abstract
Corrosion and its prevention is an important aspect of materials studies. This paper presents results of simple experiments developed for use in a time-limited course. Conventional corrosion rate experiments are time consuming, but yield useful corrosion rate data that can be used for design considerations. The lab work described here is oriented toward rapid, visual results that can be correlated to the effects of material structure, grain size, etc.

Procedures and techniques are presented describing how to perform these simple experiments and listing the equipment needed. Typical results are presented along with explanations of the anticipated results. Potential pitfalls are discussed. Student comments are also provided. The paper includes photographs of typical results.

These experiments also help the student to develop powers of observation and reporting as well as teach them something about the corrosion process.

Introduction

The effects of corrosion are obvious all around us. The etching of metallurgical samples and the way a battery works are examples of electrochemical processes. Visit a junk yard and observe the rusted hulks that were once someone's shiny new car. Non-functional farm machinery often litters the landscape because it costs too much to haul it away to a landfill. Those of us living in the rust belt wax the exterior of our vehicles, and often pay someone to provide a rust protective coating on the underside of them. Approximately 20% of the iron and steel products manufactured each year are used to replace objects that have been discarded due to rust damage[1]. Figure 1 is a photograph of a truck ravaged by corrosion typical of damage brought primarily by road salt used for winter de-icing.

Figure 1. An older vehicle shows the effects of corrosion

The Purdue University School of Technology requires all AS and BS degree Mechanical Engineering Technology students to take a sequence of materials-related courses. The first course covers metals, plastics and ceramics. Several years ago, it occurred to the author that there should be some way in the first course, to demonstrate the effects of galvanic corrosion in a simple way, that would not cost much, nor take a long time to see visible results. Over the course of four years, the author has developed methods of demonstrating in a qualitative way the effects of corrosion and to show how it can be prevented. Since our students do not have chemistry until the junior year, the lecture material covers the essentials of galvanic corrosion and the chemistry involved. Quantitative corrosion testing takes a great deal of time and utilizes nasty corrodents, like boiling sulfuric acid, to measure corrosion rates. The experiments described here provide almost immediate visual results for the students.

Background Information

Our students have already learned how cold working of a metal produces strengthening and also results in large grains being broken into many smaller grains. They have also learned about recrystallization through heating. In addition, instruction has been given concerning the formation of passive layers in stainless steels and other similar materials. In the corrosion unit, the galvanic series is introduced and it is shown how materials that are higher in the series will corrode preferentially to materials that are lower. Essential to the discussion are the five conditions that must be present simultaneously before corrosion can occur[2]. These conditions are:

1. there must be an anode where a metal is oxidized.
2. there must be a cathode where some ions are reduced.
3. a potential (voltage) must exist between the anode and cathode, usually provided by dissimilar metals.
4. there must be an electrolyte in contact with both anode and cathode.
5. there must be a physical electrical connection between the anode and cathode to complete the circuit so that the electrons can flow.

For our students, it is necessary to emphasize that oxidation is a process whereby a material loses electrons and reduction is a process whereby a material gains electrons[3]. Several textbooks illustrate this process using classical electron flow.[4] Electrolytes are usually liquids that conduct electricity, although certain solid oxides can act as electrolytes as well as some vapors[5,6]. It is important that the students understand all of these concepts in order to evaluate the results from the laboratory demonstration. The tie-in between cold work, anodes and cathodes is then made, describing how cold work simply creates large numbers of anodes and cathodes, which are essential for galvanic corrosion to occur. The anodes are the grain boundaries and the cathodes are the grains[7]. As the anodes are consumed, the grains and boundaries exchange roles, reversing the polarity. This interchange continues until the entire material has been consumed. Since the iron oxide crystal is larger and less dense than the steel crystals, the oxide buckles as it is formed, exposing fresh steel to corrosion.

Corrosion Demonstration Samples

There is an endless list of materials which could be used to demonstrate galvanic corrosion and its prevention. It is important to keep the list relatively small to prevent overloading the students with observations to make. It is also important to limit the list to materials that are readily available. We are fortunate at our location to have a supply of tensile test specimens for numerous materials. We selected a number of these for use as corrosion samples, as well as common hardware items available at reasonable cost from local sources such as hardware stores. Table 1 lists some candidate materials that can be used for the corrosion demonstration. Not all of these items should be used for one demonstration. If class size is large, it is desirable to divide the class into groups and limit the number of samples to be observed to about six or eight.

Table 1. Candidate Corrosion Materials

AISI 1010 Hot rolled steel tensile sample
AISI 1010 Hot rolled steel tensile sample, one side ground
AISI 1010 Hot rolled steel tensile sample with MIG weld bead
AISI 1010 Hot rolled steel tensile sample with magnesium strip attached
AISI 4340 Cold rolled steel tensile sample
Common steel nails, one bent, one straight
Brass tensile sample, CA 360, half-hard
Aluminum tensile sample, 6061-T6
Copper tensile sample
Inconel tensile sample
Hastelloy tensile sample
Bright zinc plated steel hardware, such as an "S" hook
Punched zinc coated steel strip used for shelving
Hot-dipped zinc coated roofing nail
Cadmium plated bolt or screw
Stainless steel bolt

Suggested Corrodents and Containers

Glass jars are best to hold the electrolyte selected to permit easy access for students to view the corrosion activity. Spaghetti sauce jars, with plain sides, work best for visibility and allow photographs to be made. The jars are carefully washed, labels are removed and all traces of glue cleaned off before use. In response to student comments, labels are provided that clearly explain what material and what corrodent is in each container.

One can choose from a large number of common liquids to be used as corrodents. Good results have been achieved with common household bleach, diluted 100:1 with water. Ordinary tap water has been used, although distilled or even deionized water would give better control of results. Other materials including calcium chloride solution (similar to road salt), ammonia, drain cleaner, dilute hydrochloric or sulfuric acids could be used with selected corrosion samples.

General Experimental Procedure

It is important to clean the samples, removing any oils that might be on the surface. An alcohol wash is a good idea. Each sample material is suspended in the glass jar using nylon fishing line, poly string or polyethylene film. In each case, the string is held by the jar lid. If significant evolution of gas is anticipated, clear film can be placed over the jar opening and the string secured with a rubber band. It is suggested that the jar be filled with the corrodent before inserting the sample. A good cover is needed to prevent evaporation. For the tensile specimens, a small hole is drilled in each one, allowing the string to be inserted. Other materials can have the support tied on or looped around.

Students are given a data sheet on which to record their observations. They are to observe the samples about one hour after immersion and every other day after that. If possible, more frequent observations for the first 24 hours might be useful. The observations are usually ended after one or two weeks. Students are encouraged to note the progress of corrosion, if any, and draw sketches. It is best if they do not touch or move the jars.

Typical Results

The results obtained from steel samples are discussed below. Results from other materials are summarized in Table 2.

Hot rolled steel samples.

Hot rolled material is protected by a black oxide coating that occurs during processing. However, since these samples are sheared, the edges have undergone significant cold work. One should see rust forming on the sheared edges during the first hour of immersion. The sample having the weld bead on it should show rust forming at the edge of weld first. This is due to cold work that occurs as the weld cools. The sample edges will not rust as rapidly in this case due to recrystallization that occurred during the welding process. The sample that has the magnesium strip attached should rust very little, but the magnesium strip may be consumed. This is of course, an example of cathodic protection, where the magnesium becomes the anode that is consumed to protect the cathode. (Most hot water heaters have a magnesium rod installed for this purpose.) Figures 2, 3 and 4 show the progress of corrosion for some hot-rolled materials after 48 hours of immersion.

If a strip with one side having the oxide layer removed is used, one will see immediate rusting of that side, but very little on the reverse side. This is the same principle as the magnesium strip, the bare side oxidizes first, protecting the other side. In one case, a student suggested applying car wax to the ground side. The corrodent quickly penetrated the wax coating. Other protective schemes can be attempted. If the sheared strips are heated to the recrystallization temperature and slowly cooled, the resulting larger grains in the sheared area should lead to reduced oxidation. Protective coatings, such as paint could also be used.

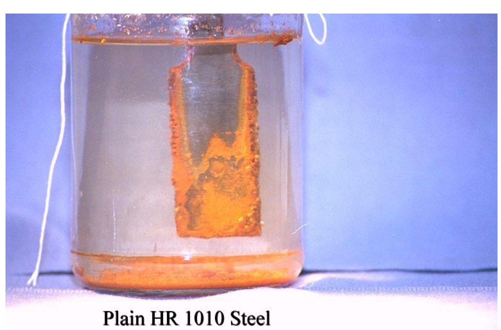
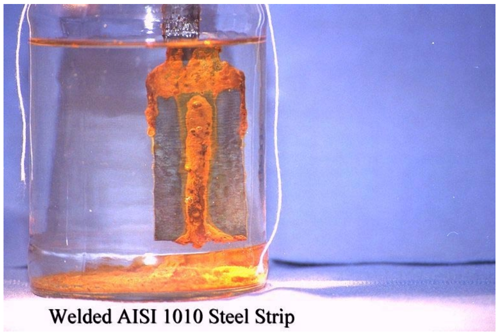


Figure 2 - Plain HR Steel Sample



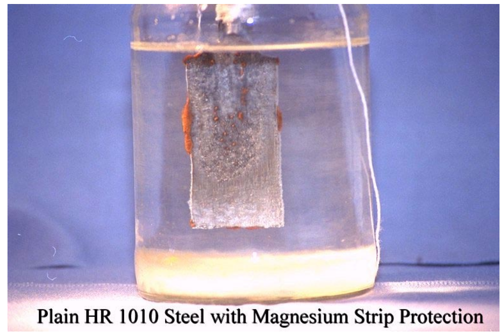


Figure 3 - Welded HR Steel Sample   Figure 4. - Magnesium Protected HR Steel Sample

Table 2. Summary of results from various materials.

Sample	Electrolyte	Results	Explanation
Cold-rolled steel	Dilute bleach	Rust forms quickly, in a uniform manner	Small grains from cold work provide more anode/cathode pairs.
Straight and bent nails	Dilute bleach	Rust forms on the heads and points, plus at the bend	Cold working causes grain size reduction, enhancing oxidation at the head and point of the nails and where the nail is bent.
Copper and brass	Dilute bleach	Little corrosion observed	Natural passivity protects copper and its alloys. Some oxides are observed above the liquid line due to high oxygen level in air.
Aluminum	Dilute bleach	Clumps of white material appears after some time.	This material is either aluminum oxide or chloride.
Aluminum	Household ammonia	Rapid evolution of bubbles, a dark layer forms on the sample, bubbling ceases after some time	This is a self-anodizing reaction, forming a layer of aluminum oxide which protects the metal from further reaction.
Zinc coated and plated steel materials	Dilute bleach	Bright plating dulls, but even punched plates do not rust.	Zinc is a sacrificial anode. Even scratching the surface will not promote rusting.
Cadmium plated hardware	Dilute bleach	Plating becomes dull, but no rusting occurs.	Same as above.
Inconel and Hastelloy	Dilute bleach	No reaction	These materials are relatively immune to oxidation.
Stainless steel bolts	Dilute bleach	No reaction	Stainless exhibits passivity due to its chromium content.

Student Reactions

Some typical student comments from the Fall, 1996, semester are included below.

"The corrosion lab, in my opinion, was very interesting, but more time was needed for observation."
"The corrosion lab was an excellent example of the corrosion process. Overall, the content and knowledge gained from this lab was excellent."
"The chemistry stuff was hard, since I haven't had it yet."
"I liked the 'eyes on' aspect of the lab. Real life is more convincing."

In general, student comments are very favorable to the laboratory even though they do little but observe the processes. Students made these comments anonymously and were told they would have no effect on their grades for the course. These comments indicate that the lab is well worth doing. These experiments also help the student to develop powers of observation and reporting as well as teach them something about the corrosion process.

References

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