MATERIALS EXPLORERS™

THE MATERIALS THAT MOVE US: CHEMICAL AND PHYSICAL PROPERTIES

(Photo courtesy the U.S. Library of Congress Prints and Photographs Division.)

Distinguish between chemical and physical properties through real-world examples of each. Learn about chemical changes by watching corrosion at work then see how ship failures in World War II led to improvements in how we test materials.

In this module students will be able to:

- Identify both physical changes and chemical changes
- Recognize corrosion as an example of a chemical change and identify different examples of corrosion
- Recognize the importance of understanding physical properties when working with a material
- See how scientists and engineers learn from failure to improve their understanding of a material
- Explain what a coating is, provide examples of coatings used in industrial applications, and identify the physical and chemical properties of those coatings

Class Activity

CORROSION AND COATINGS

Background

From ice melting to food digesting, you encounter physical and chemical changes on a daily basis but can you distinguish one from the other?

By definition, a **chemical change** requires that the atoms of one or more substances are rearranged to create a new substance with a different chemical composition. In a chemical change, some of the bonds between the electrons of atoms will break or reconnect in different patterns. In contrast, a **physical change** may alter the substance's physical properties (such as shape, size, state or appearance) but the substance itself remains the same. To understand these concepts more easily, think of the following real-world examples.

All changes of state such as ice cubes melting or alcohol evaporating are physical changes because the properties of the materials themselves do not change. The water and alcohol are still the same, but they exist in different forms. On the other hand, baking a cake or burning paper are considered chemical changes because they result in the production of a whole new compound. After all, a finished cake has very different properties than all of the individual ingredients used to produce it.

Another common example of a chemical change you may see every day is **corrosion**. Corrosion is the deterioration of a material due to a chemical reaction between it and its environment. One example is steel rusting. A major component of steel is the element iron (Fe). When iron comes in contact with oxygen (O), such as from moisture in the air, it undergoes a chemical reaction to become iron oxide, Fe_2O_3. Since there is always some moisture in the air, if no action is taken, over time all the iron in the steel can be consumed in the chemical reaction to form rust. As you can imagine, this deterioration is a major concern to manufacturers and to people everywhere who use these products.

It is possible to add elements into the **alloy** to help protect it from corrosion. For example, stainless steels are a group of steel alloys that have chromium added to them to help prevent rusting. Another way to prevent corrosion is through **surface engineering**, which is an interdisciplinary field combining aspects of materials science, chemistry, physics, process engineering, and chemical engineering to make materials more robust by protecting them at the surface level. In the example of iron reacting with oxygen to form rust, it is possible to put a surface coating on the steel to prevent oxygen from reaching the iron atoms, and thus prevent corrosion.

Class Activity

When vinegar is added to baking soda a chemical change takes place because an entirely new product is being formed. The baking soda (sodium bicarbonate) and vinegar (acetic acid and water) react to form carbon dioxide gas and sodium acetate. The bubbles that form are actually the carbon dioxide being released.

Corrosion is a serious concern when working with steel. In fact, a 2002 federal study by NACE International indicated that corrosion affects nearly every U.S. industry sector and, at the time, created cost the U.S, $276 billion a year! A lot of this money goes into inspection, maintenance, and repair.

The first step to designing a successful surface treatment is understanding what function the product needs to serve. In some cases, scientists and engineers are tasked with making attractive yet durable products (imagine a shiny bathroom faucet). In other cases, the appearance does not matter at all (as with a large pipe that will be buried underground), but the product's surface must withstand use in very harsh environments or protect against corrosion, chemicals or heat.

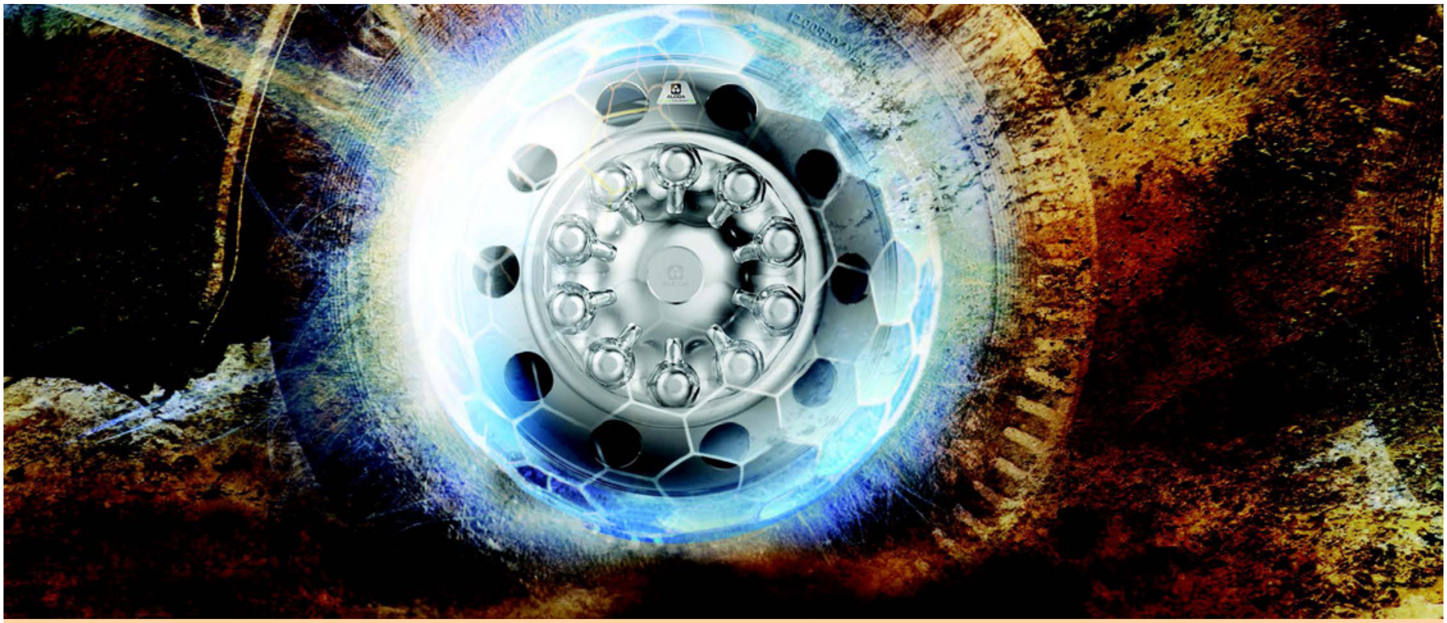
The second step to designing a successful surface treatment is understanding how your substrate material and the surface treatment process will interact. For example, cleaning your substrate first will help a coating stick, but using an improper chemical might damage the appearance of the surface. Scientists and engineers rely on a thorough understanding of the processes and materials being used to help determine the right course of action.

The last step in designing a successful surface treatment is testing the product against customer requirements. Usually this is done in an accelerated manner in the laboratory. For example, if the final product will be exposed to erosive elements (as with a car driving through a sandy desert) a test where it is exposed to abrasives such as blast media or sand paper can help to predict the part's performance once in use. Extensive testing ensures that the final product meets customer requirements.

Class Activity

To gain a better understanding of engineered surface treatments, consider the example of the Dura-Bright® surface treatment on the Alcoa Wheels commonly used by commercial vehicles. The Dura-Bright® surface treatment was developed by Arconic to protect aluminum vehicle wheels. Aluminum is used because it is lighter than steel—and a lighter wheel means improved fuel efficiency and a potential increase in payload capability. However, wheels used on tractor trailers are exposed to road salt, gravel, sand, and cleaning chemicals, all of which can cause aluminum to corrode, thereby degrading both the appearance and the performance of the material.

So how can Arconic promise customers the benefits of aluminum wheels without an increased risk of corrosion? The Dura-Bright® surface treatment forms a protective barrier on the aluminum wheels to help it resist the corrosive effects of harsh environments. This surface treatment also protects against other chemical attacks, abrasion, and scratching. Additionally, Dura-Bright® is engineered to have a low surface energy that makes the wheels easy to clean with only soap and water, keeping them looking bright and shiny with low maintenance costs. This is surface engineering at work.



Surface engineering has made it possible for the Alcoa Wheels to gain the benefits of an aluminum wheel, without the risk of corrosion. (Photo courtesy of Arconic.)

Problem:

Many automotive companies are switching to making car frames out of aluminum rather than steel because aluminum is a lightweight metal and less weight generally translates into greater fuel efficiency. A major automotive company is considering making this switch, but has expressed concerns over the possible corrosion of the aluminum frames. The company has asked you to investigate one of the conditions that might cause aluminum and steel to corrode.

Class Activity

Task:

You and your partner are tasked with recording the pH of various solutions and predicting at what pH levels aluminum and steel might begin to corrode.

Procedure:

1. Using pH paper, record the pH of the following substances:
    a. Carbonated soft drink
    b. Orange juice
    c. Acetone
    d. Milk
    e. Energy drink
    f. Car wash concentrate
    g. Shampoo
    h. Water
    i. Salt water

2. Use the pH data collected to predict which types of conditions will cause corrosion for aluminum and for steel.
3. After observing the demonstrations conducted by the teacher, obtain 9 squares of aluminum prepared by the teacher (be careful—the edges may be sharp) and gather 9 paperclips (steel).
4. Label 9 containers (one for each of the available substrates in step one) and place one square of aluminum and one paperclip in each.
5. Place 15-30 drops of each substance in its corresponding container.
6. Set aside your containers where they will not be disturbed,
7. Create a data table to record which solutions, if any, caused the aluminum and steel to corrode. Check the squares for corrosion at the end of the class period, and once a day over the course of a week. For each solution, record when you begin to see evidence of a chemical reaction or corrosion on the foil or on the paperclip. This evidence may be noticed as a color change, change in the surface roughness of the material, an extra layer being deposited, or pits/erosion of the surface.

Questions

1. **Based on your observations in this experiment, would you classify corrosion as a physical or chemical property? Justify your answer with evidence.**

2. **Based upon the observations made during your experiment, what conditions caused the aluminum to corrode? Are there any recommendations you would make to the car manufacturer to help them avoid corrosion?**

Class Activity

3. **Based upon the observations made during your experiment, what conditions caused the steel paperclips to corrode? How did these results vary from aluminum and what does that indicate about the properties of steel?**

4. **Corrosion is just as important to consider when developing packaging for the food and beverage industry. Research two types of coatings used in this industry and explain the types of products that use these coatings.**

5. **The effects of corrosion also impact many structures and buildings. In fact, some statues have become faceless over time due to the effects of acid rain.**
   - **i. Research the causes of acid rain.**
   - **ii. Identify a statue or building that has been impacted by acid rain and explain the acid rain's impact on that structure.**
   - **iii. Not all materials are easily damaged by acid rain. Identify three materials that you would recommend to sculptors who wish to make their art more durable.**

Definitions

Alloy
A material composed of two or more metals or of a metal and another element.

Chemical Change
A change that occurs when one or more substances change into entirely new substances with different properties.

Corrosion
The process by which a material deteriorates due to a chemical or electrochemical reaction with the environment.

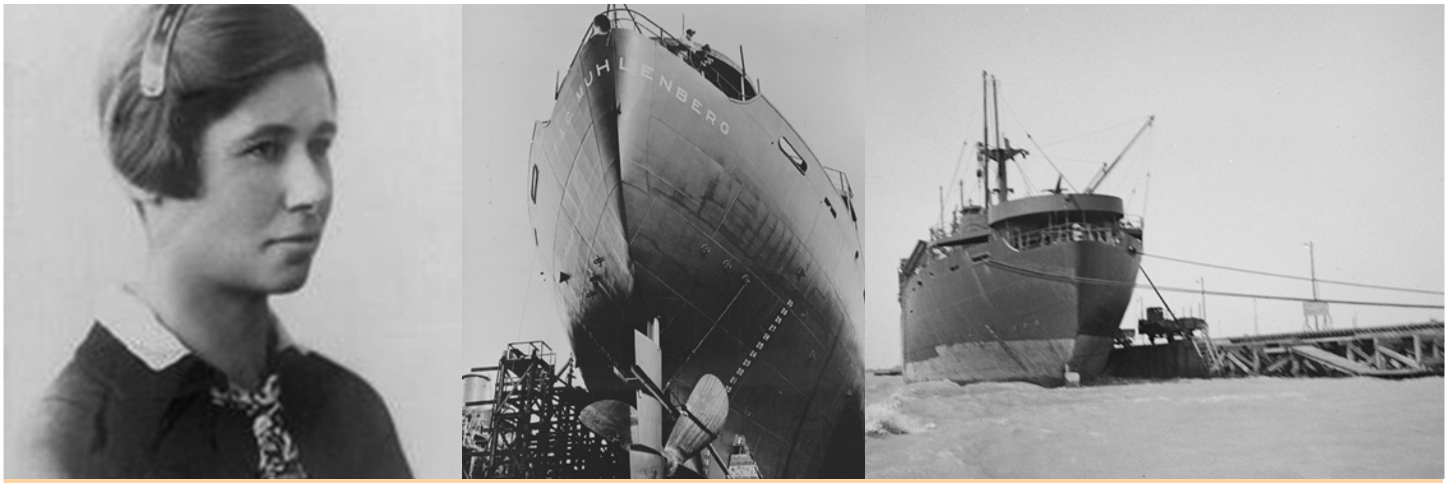
Physical Change
A change of matter from one form to another without a change in chemical properties.

Substrate Material
The material that is being surface treated.

Surface Engineering
An interdisciplinary field aimed at making materials more robust by protecting them at the surface level.

Extension Activity

Learning from Our Mistakes



Constance Tipper was able to solve the mystery of why the Liberty Ships were suddenly and catastrophically failing in use thanks to her research on the temperature at which steel became brittle. (Photo courtesy the U.S. Library of Congress Prints and Photographs Division.)

Try as we might to avoid them, mistakes happen. What matters is learning from those mistakes in order to avoid repeating them. The same is true within engineering as we owe some of our standard practices, and even legal regulations, to the lessons learned from earlier failures. With German U-boats rapidly sinking British ships during WWII, the United States developed a way to mass produce cargo ships to carry vital supplies to the British army. Instead of riveting together the slabs of metal that made up the ship, the shipyards simply welded the pieces together. This cut production time by months, making it possible to produce a ship in just 42 days. There was just one problem—the ships were failing catastrophically. In the cold ocean waters of the North Atlantic, some of the ships literally broke in half after developing cracks that instantly traveled the whole way around them.

The Liberty Ships Problem

Researching failures can help revolutionize the way we develop or use various materials; transform design philosophies; establish strict guidelines for inspection, testing and maintenance of structures; and even give birth to entirely new fields of study. Consider the example of the World War II "Liberty Ships" which, because of poorly understood material properties, had an unfortunate habit of breaking in half.

In trying to determine the cause of these failures suspicion naturally fell on the radically new approach of an all-welded pre-fabricated ship. Then Constance Tipper entered the picture.

Constance Tipper

Constance Fligg Tipper (née Elam) was born February 6, 1894, and distinguished herself early on by becoming one of the first women to take the Natural Science Tripos (the framework within which most of the sciences are taught at the University of Cambridge) at Newnham College, Cambridge. From there, Tipper

Extension Activity

went on to work briefly at the Royal School of Mines (part of the Imperial College London) where she was a research student working with Henry Cort Harold Carpenter on crystal growth and recrystallization in metals. This early research with Carpenter turned out to be foundational work in the field. Tipper next went on to work with G.I. Taylor at Cambridge where she once again was a part of groundbreaking work. Tipper continued her work in this area, publishing *The Deformation of Crystals*, a book that became the most commonly referenced work on the subject at the time.

Despite her success, Tipper struggled to gain recognition within a male dominated field. In fact, she continued her research at Cambridge for many years without holding an official title! Eventually, she gained her long overdue recognition and became a lecturer in the Faculty of Engineering and leader of the department's Heat Treatment Laboratory. It was at this stage in her career that she was consulted as a technical expert on the Liberty Ships dilemma.

Cracking the Case

Tipper, who at this point had spent years investigating the failure of metals, obtained a sample of the failed ships for testing. She suggested that the fault did not lie with the welding at all, but with the steel itself. She demonstrated that there was a temperature at which the steel became **brittle** rather than **ductile** and that the cold waters of the North Atlantic were causing the ships to rapidly fracture. In materials science the word "brittle" means that when a load is applied to a material, it will not stretch but will fracture suddenly (think of dropping a ceramic mug). "Ductile" means that when a load is applied, the material will be able to stretch and deform some before finally breaking (think of crushing an aluminum can). Some materials have a transition temperature where they are ductile at higher temperatures but can become brittle at low temperatures; the steel of the ships was such a material. The temperatures in the region where the ships were manufactured was high enough for the metal to be ductile. However, when the ships passed through much colder waters, the metal became brittle and a change in stress, a pre-existing flaw, or a small crack would lead to a catastrophic brittle failure of the ship.

In the course of the investigation of the Liberty Ships, Tipper developed a test that became the standard method for determining brittleness in steel—now commonly known as the "Tipper test." Tipper didn't just identify what had gone wrong, she showed the shipyards how to test the steel and prevent the failure from reoccurring. Even more critically, her work established the field of **fracture mechanics** that continues to be a critical field within engineering.

The case of the Liberty Ships just goes to show that, even when we think we know all of the physical properties of a material, there may still be factors we have not considered. While the problem of the Liberty Ships is a dramatic example of a material failure leading to improved understanding, it's important to know that many material failures take place on a much smaller scale or within the controlled environment of laboratories. Like Constance Tipper, today's engineers research these failures to understand why they occurred and, more importantly, ensure that they never pose a risk to individuals.

**Parts of this article are excerpted from "Constance Tipper Cracks the Case of the Liberty Ships" by Kelly Zappas, published in JOM, December 2015, Volume 67, Issue 12, pp 2774-2776*

Extension Activity

Questions

1. Mechanical, physical, chemical, and manufacturing properties directly influence material selection in engineering. List an example of each property.

2. Constance Tipper discovered that at a certain temperature steel becomes brittle as opposed to ductile. This transition temperature is different for every alloy of steel. Research one specific steel alloy and its ductile to brittle transition temperature. List the name of the steel, its transition temperature, and the source where you found the information.

3. Ships initially made from timber transitioned to iron and then steel. Based on your observations from the activity and research, why is it unlikely that ships will eventually be constructed from aluminum as opposed to steel?

Definitions

Brittle
A brittle material will break suddenly rather than deform when a load is applied.

Ductile
Able to be drawn into a thin wire without becoming weaker or more brittle.

Fracture mechanics
Mechanics of solids containing cracks with a focus on a crack's growth.

MATERIALS™ EXPLORERS

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ARCONIC FOUNDATION

Materials Explorers™ is a STEM educational outreach initiative of The Minerals, Metals & Materials Society (TMS). TMS is non-profit, international professional society with a mission to promote the global science and engineering professions concerned with minerals, metals, and materials.

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