

Corrosion and Its Challenges for the Mechanical World

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Sometimes corrosion is attractive. For example, the vivid colors on titanium jewelry are oxides, with the color difference the result of the oxide thickness and the refracted light. Also, from an artistically oriented viewpoint, the golden-brown appearance of many of the new high-voltage towers made from ASTM A 242 (Corten) steel is more appealing than their bright galvanized cousins, and that “pleasing brown color” is a tightly bonded coating of rust. But most of the time, and in several ways, corrosion presents difficulties that can greatly shorten the life of mechanical equipment.

Typically, as engineers and technical people, we know that steel corrosion involves oxygen atoms uniting with the iron atoms in the steel. We realize this reaction slowly thins the base metal, and that the steel or iron part could eventually crumble into a pile of rust. But there are also times when the very serious dangers from corrosion are almost invisible to the human eye.

Two general classifications for corrosion are:

- Dry—at elevated temperatures.
- Wet—where liquid is needed to conduct corrosion currents.

An example of dry corrosion is the scale that develops on grates of a barbecue grill. In those situations, the elevated temperatures supply the energy needed for the oxygen to unite with iron. Fortunately, dry corrosion is uncommon in the machinery world because the temperatures needed for it are in the range where specialty alloys and exotic lubricants are usually needed.

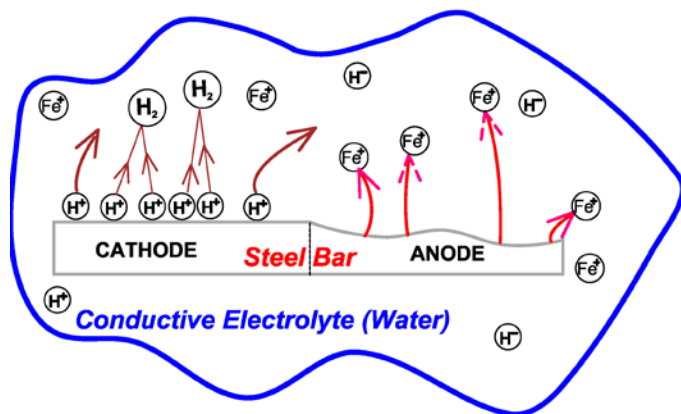


Figure 1—Microscopic view of a corrosion cell on a steel bar, illustrating how differing electrical potentials create an anode where iron ions are released and a cathode where hydrogen gas forms, initiating the rusting process.

To understand wet corrosion and the problems it can create, Figure 1 shows a microscopic view of what happens in a typical corrosion cell. This shows the corrosion of a steel bar, and because of minute differences in the electrical potentials within the bar, the anode area is being attacked while the cathode area is protected. At the anode, Fe^+ (iron) ions are released. (An ion is an atom with an electrical charge.) They are off in the liquid, usually water, and will eventually pair up with some oxygen ions to form the various forms of rust that we see all around us.

Only a very short distance along the bar is the cathode, where the hydrogen ions, from the water H_2O molecules, are being liberated. As shown in the diagram, most of those ions rapidly find another ion and form hydrogen gas. However, there is always dissociation and some of those hydrogen ions wander off to do later damage.

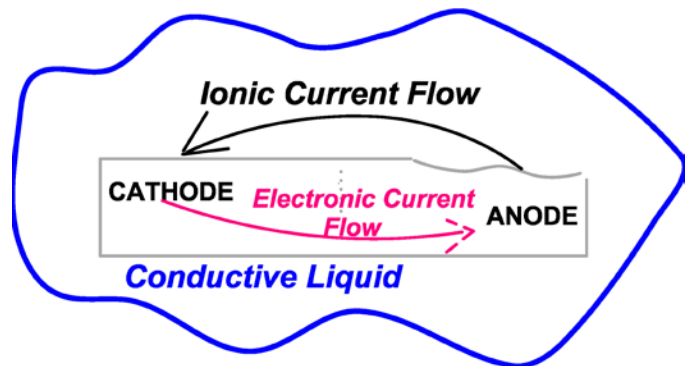


Figure 2—Corrosion circuit in a steel bar, showing electron flow through the metal and ionic current through a surrounding liquid, highlighting the necessity of moisture for corrosion to occur.

Going back to that steel bar, as shown in Figure 2, the internal electric charges flow from the cathode to the anode, and then, to complete the corrosion circuit, the ionic currents flow back through the liquid. From this figure we can see that there has to be liquid present to conduct the currents that result in the corrosion.

Unfortunately, that doesn't mean the part has to be dripping in water, and we've all had cases where a relatively clean piece of steel has emerged from a long seclusion in desk drawer with a light coating of rust. It turns out that, due to intermolecular forces, corrosion can begin at only 60 percent relative humidity.

It's also interesting that, the more conductive the liquid, up to a point, the more rapid the corrosion. That's

because a more conductive liquid, such as salt water, can more effectively carry the corrosion currents.

The problems that corrosion can cause are three-fold:

1. **Material loss**—There is a loss of material and contamination of the product surface. Usually this is readily visible and, although it can be expensive to correct, it is readily detectable.
2. **Hydrogen damage**—This type of corrosion damage goes by various names such as hydrogen embrittlement, hydrogen cracking, and stress corrosion cracking, and there are some differences in the exact mechanisms. However, the basic cause is those free hydrogen ions can result in unexpected and undetected fractures.
3. **Reduced fatigue strength**—Corrosion continually reduces the fatigue strength of the metal. The more severe the corrosion, the faster the fatigue strength is decreased, and that continual reduction in fatigue strength essentially goes on forever.

(It's important to realize that corrosion isn't the only source of the free hydrogen atoms that result in hydrogen cracking. Some of the other processes include steam leaks, plating processes, acid cleaning, welding, etc. Still, corrosion is unique in that it continually generates hydrogen and doesn't have the recognition and controls of the other processes.)

Scientists have been trying for years to understand exactly how hydrogen and the other chemicals, especially sulfur, interact to cause cracking and the reduction in fatigue strength, and the primary source of the problem

appears to be those hydrogen atoms, their need to form hydrogen molecules, and the relative sizes of different atomic structures.

A hydrogen atom, with only one electron, is tiny compared to the rest of the atoms in our universe. A simple example of how a hydrogen atom can cause the cracking is to think of it as the size of a golf ball and the structure of iron and steel as being made up from neatly stacked atoms the size of bowling balls. The single golf ball, i.e., a hydrogen ion, can easily move in between the bowling balls with no problem. But then it meets another hydrogen ion and the atomic forces cause it to form molecular hydrogen, H_2 , the gas we're familiar with. However, the hydrogen molecule is about five times larger than the hydrogen atom and that causes stress within that assembly of "neatly stacked bowling balls."

H_2 molecules tend to group together at irregularities within the metal's structure. Then, as more and more hydrogen molecules are formed, the stress inside the steel structure increases, and the material's ability to withstand external stresses decreases.

Hydrogen Damage and Cracking

With ductile metals, such as low carbon steel, the material can easily deform and the reduction in strength isn't terribly significant. Figure 3 shows a piece of SAE 1020 steel with a series of blisters that are about a quarter inch in diameter and are filled with hydrogen. It was part of some chemical process equipment and wasn't highly stressed so the blisters didn't cause any problems, but larger blisters can cause reduced ductility.

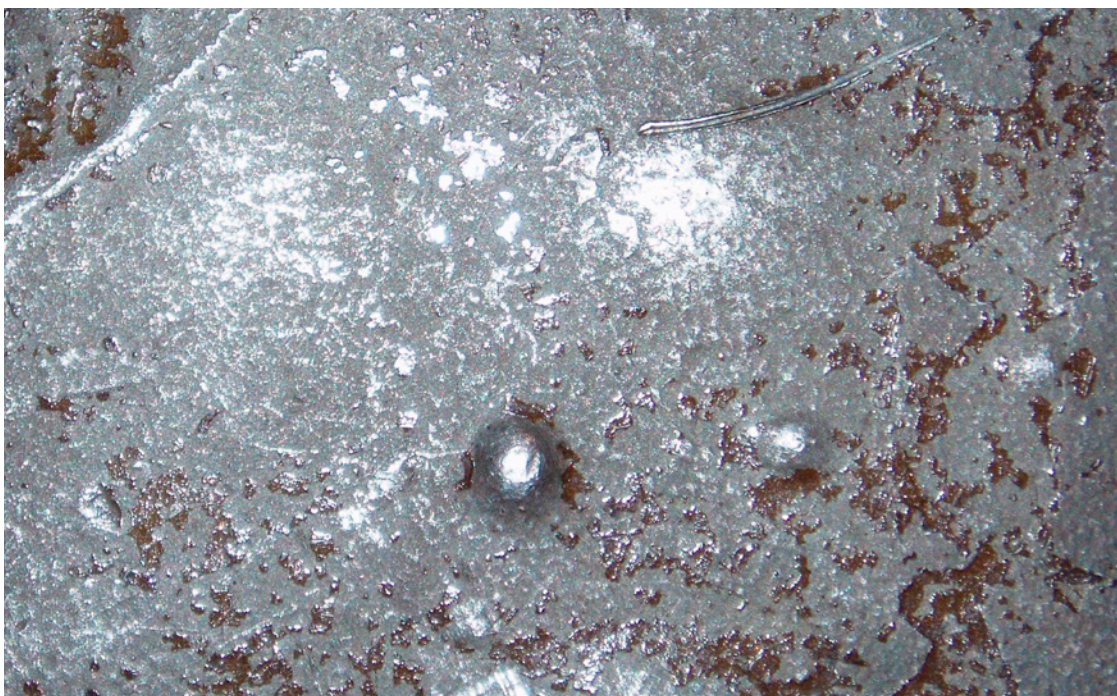


Figure 3—Surface blisters on SAE 1020 steel caused by trapped hydrogen—common in ductile metals and typically harmless under low stress, though larger blisters can reduce material ductility.

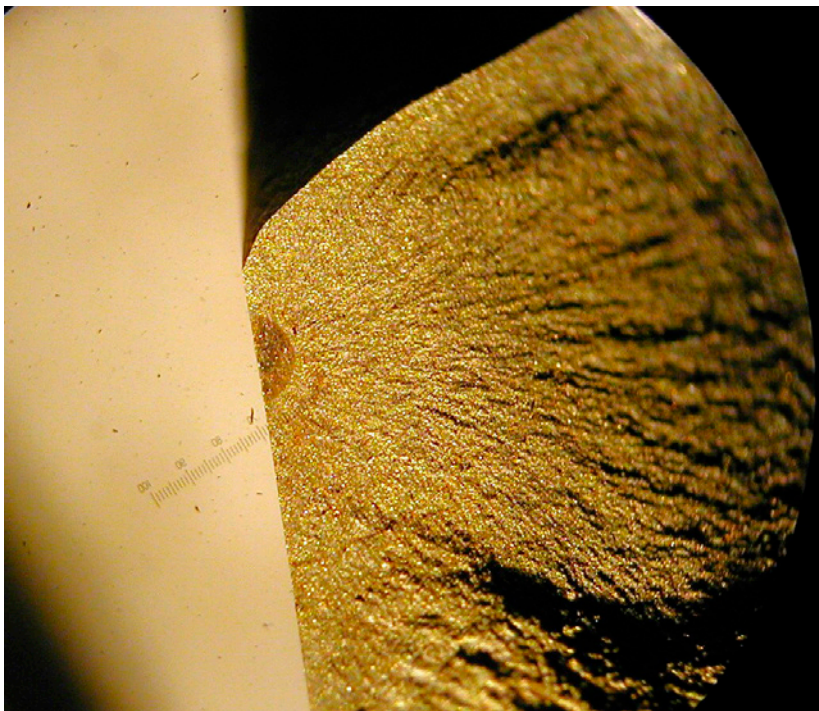


Figure 4—Magnified fracture of a high-strength steel spring (HRC 50), showing corrosion-induced cracking from hydrogen embrittlement—originating at a rusted area caused by cleaning and poor design.

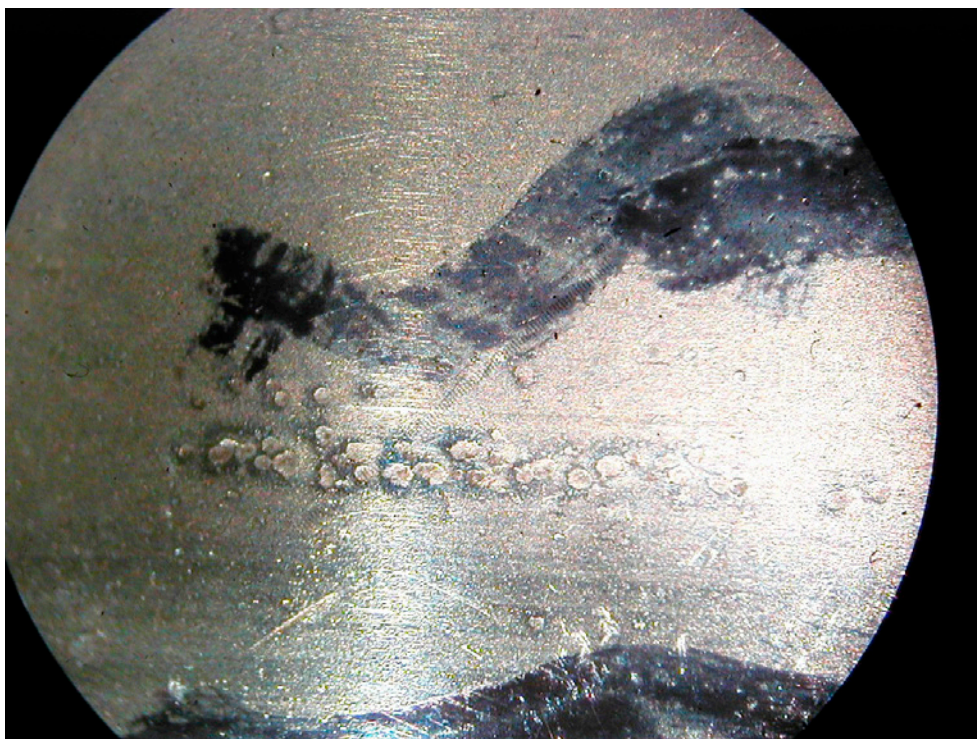


Figure 5—Microscopic view of corrosion pits on a roller bearing raceway, the small round pits between the two heavy black pen marks were caused by corrosion.

However, as steel is processed to become stronger, it almost always becomes less ductile and the effect of the atomic hydrogen becomes more critical. Figure 4 shows the magnified fracture of a steel spring used in a piece of pharmaceutical equipment. The bottom of this HRC 50 spring was rusted, the result of the cleaning process and a poor machine design. Looking at the crack face, the corrosion at the origin is readily visible, and a metallurgical analysis confirms that hydrogen was involved.

We know that hydrogen cracking is the result of a combination of metal chemistry, temperature, stress and time. Nevertheless, the only way for sure to know if hydrogen has contributed to a failure is to have the part analyzed for hydrogen content, but there is no hard and fast rule as to the effect that corrosion has on causing the failures.

One of my first lessons about the effect of corrosion involved a \$200,000 roller bearing in one of our machines. This was before the era of predictive maintenance, and we had removed it from position and opened it up to inspect the condition of the contact surfaces. The cause of the problem was that, after removing it from a very dirty environment, we had washed it with hot water that managed to get past the seals. So, when we opened the bearing there were a series of black marks on the inner and outer rings, and Figure 5 is a microscope's view of the marks. They are corrosion pits and the technical staff from the bearing manufacturer told us that the hydrogen from the pitting had reduced the L10 life of the bearing to 10–20 percent of the original.

Black marks on the contact path of a rolling element bearing are almost always symptoms of corrosion that will greatly reduce ball and roller bearing life. With similar stress mechanisms and hardened steels, corrosion will also reduce the life of gear teeth and chain components.

Fatigue Life Reduction

While one type of corrosion-generated hydrogen damage usually causes relatively sudden fractures, we know that another causes a continuous reduction in fatigue strength.

In the book *Fatigue Design* (John Wiley & Sons, 1970) by Carl C. Osgood, he cites numerous tests showing how corrosion affects the fatigue strength of various metals. Ironical is that, with steel alloys, the stronger the alloy, the greater the reduction in fatigue life. One of the book's charts shows that a 60,000 psi steel has a 39 percent reduction in fatigue strength while, with identical conditions, a 130,000 psi steel has a 66 percent reduction.

From a practical standpoint, there is good data showing that even a humid atmosphere will result in a significant reduction in fatigue strength and eliminating that surface corrosion is beneficial. (With this knowledge, we wrapped a series of 145,000 psi (1 GPa) machine shafts with vinyl tape and found a five-fold increase in average shaft life.)

Most fatigue design involving steel alloys is based on a given fatigue strength that doesn't decrease after 10^6 or 10^7 cycles; however, corrosion will continually reduce the fatigue strength until the cyclically loaded part will eventually fail.

PTE



Neville Sachs, P.E., is a Stevens Institute of Technology graduate and renowned expert in mechanical failure analysis. He has authored three books, contributed to four others, published over 60 technical papers, and taught industrial failure analysis across North America and Europe since 1987. He is active in ASME, STLE, NSPE, and AMPP.

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