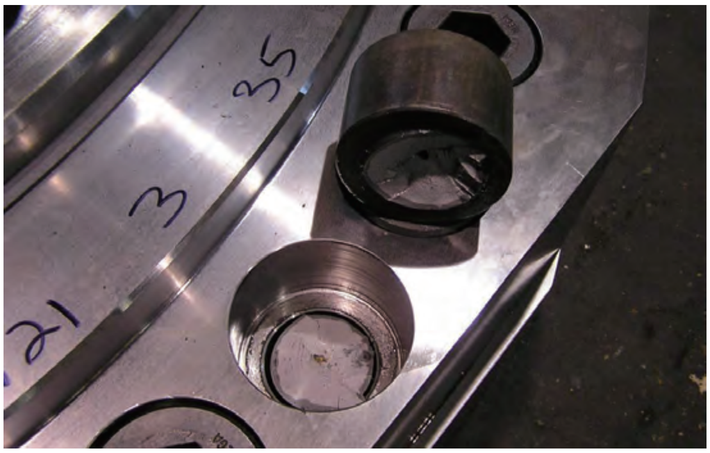
Hydrogen Embrittlement

by Laurence Claus

If you are in the fastener industry long enough you will eventually experience first-hand or hear stories about a hydrogen embrittlement failure. In fact, the fear of this potential failure is so palpable that many of the stories have taken on urban legend status. Although many of these stories may not be as exceptional as they are made out to be, there is no denying the fact that a hydrogen embrittlement failure can be painful to all the parties involved.



A Socket Head Cap Screw that has Failed by Hydrogen Embrittlement (used with permission of SV Brahimi)

One might ask why a hydrogen embrittlement failure is any worse than other fastener failure. This is a good question. Perhaps one would argue that it is no worse than any other, we all understand that a failure is a failure. However, others might argue that it is worse because it comes with no warning and its fallout is completely unpredictable. In one case, it might affect almost an entire lot of parts but in another only a small percentage. Additionally, although parts can have all the ingredients for a problem, it only strikes after the parts are put into service. This makes such failures especially difficult because containment and restoration is often extremely costly.

The good news is that with the billions of fasteners produced every year, the actual incidence of problems is quite small. In fact, the actual number of hydrogen embrittlement incidents, even in parts seemingly quite susceptible, is generally rare. Thus, recent research suggests hydrogen embrittlement susceptibility of fasteners is, perhaps, less than traditionally assumed. The actual rarity of problems in the field seems to buttress these results.

With that said, however, problems do occur. One recent and high profile incident occurred several years ago in the United States during the construction of the state of California's new east span of the San Francisco and Oakland Bay Bridge. The bridge, first constructed in 1936, consists of two spans, a west span that connects the city of San Francisco with Yerba Buena Island and an east span that connects Yerba Buena Island with the city of Oakland. On October 17, 1989 the Loma Prieta earthquake hit California's Bay Area. This earthquake was a 6.9 on the Richter scale and ended up collapsing a fifty foot section of the existing east span. Since this bridge is a major transportation artery, immediate repairs were made but the state of California Transportation Department (Caltrans) decided that for long-term purposes they should replace the east span with an all-new bridge.

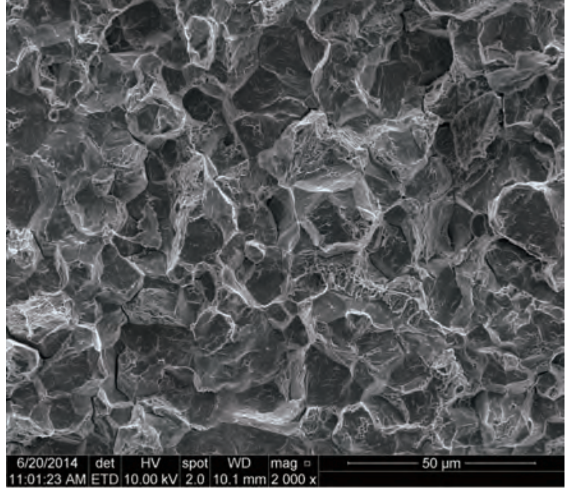
As Caltrans sat down and designed what they wanted in a new bridge they came up with two unique requirements. First they decided that the bridge must have a life span of 150 years, or almost double the life span of a normal bridge. Secondly, the bridge needed to be designed to withstand a 1500 year seismic event. This type of event equates to a massive earthquake.

As Caltrans was forging some new territory with these extreme requirements, they had to adapt some new practices and designs. To meet the 150 year lifespan requirement much of the hardware was given protective coatings including the ASTM A354 anchor rods, which were hot dip galvanized. Although the ASTM standard does not prohibit this practice, it is an exception to the normal practice of supplying this type of product uncoated. To meet the requirements for protection against earthquake activity the bridge was designed with a series of "Bearings" and "Shear Keys". These components, located underneath the bridge deck on one of the concrete piers were designed to transfer the forces from an earthquake into the piers rather than damage the superstructure or bridge deck. These "Bearings" and "Shear Keys" were designed to be attached using ASTM A354 anchor rods that were embedded into cavities in the concrete pier below.

These anchor rods were embedded in the concrete long before they were tightened to their final high preload. On March 1, 2013, ninety-six rods that were manufactured in 2008 were tightened on two "Shear Keys". They were tightened to just under 70% of their ultimate strength, or what fastening experts would consider a high preload. On large diameter structural product like this, it is common for the joints to be inspected and re-tightened if necessary. Therefore on March 8, roughly one week later after original tightening, several of these anchors rods were discovered to be broken. By March 15, 2013 thirty-two of ninety-six had fractured.

Naturally this failure placed Caltrans in a difficult position. They had a major problem and few answers. In fact, the problem was so severe that it threatened to postpone the planned opening, a few short months away. They neither understood what had caused the anchor rods to fracture nor had a way to repair the damaged ones. Caltrans jumped into high gear, though, simultaneously recruiting several of the industry's best experts to help determine the root cause of the problem and engaging their engineers to find a solution on how to attach the "Shear Keys".

These experts would later conclude that the ASTM A354 rods had failed by hydrogen embrittlement, writing in their public incident report, "Hydrogen embrittlement is the root cause of the A354 grade BD high strength steel anchor rods at shear keys S1 and S2..." At first, blame was cast



Scanning Electron Microscope Image of a Hydrogen Embrittlement Failure Showing the Characteristic Intergranular Brittle Fracture Morphology (used with permission of SV Brahimi)

on the galvanized plating as having caused the hydrogen embrittlement. As the examination progressed, however, the experts would eventually determine that corrosion caused by water seepage into the cavities that housed each A354 rod was the culprit for exposing the system to hydrogen. This environmental exposure to free hydrogen, coupled with clearly evident material susceptibility factors would produce a textbook case of environmental hydrogen embrittlement which ultimately failed the offending rods.

Although many organizations do not know how to respond to such problems, Caltrans stands out in the proactive and assertive manner in which they responded to this crisis. Although it would cost Caltrans many millions of dollars they were successful in opening the bridge on the originally scheduled day, Labor Day 2013, and concluded their operational fix to the "Shear Keys" by December 18, 2013. Additionally, they would go all out and investigate all 2306 A354 anchor bolts that were used on the bridge.

Certainly not all hydrogen embrittlement incidents are as costly or as high profile as this one. However, this case provides a poignant lesson for the industry to review and learn from. It also exemplifies that knowledge of how hydrogen embrittlement works and the best prevention techniques is important. The remainder of this article shall highlight some of the basics for understanding hydrogen embrittlement.

What is It?

ASTM F2078 defines hydrogen embrittlement as a "permanent loss of ductility in a metal or alloy caused by hydrogen in combination with stress, either externally applied or internal residual stress." In other words, we understand that atomic (or free hydrogen) that is absorbed by the part moves to areas of the part that are under stress. As the concentration of hydrogen increases in these areas the metal begins to behave in a brittle fashion and micro-cracks begin to form around the metal grain boundaries. If enough hydrogen collects in these areas of high stress (normally at the head fillet or the first engaged thread), and enough ductility is lost, eventually the part fractures in a brittle fashion at the offending high stress point.

There are three fundamental misconceptions that are commonly held. The first is that hydrogen embrittlement is a root cause. It is not a root cause, but rather a mechanism of failure. The root cause is almost always traced back to the material's susceptibility. The second is related to the fracture mode. A hydrogen embrittlement failure will exhibit evidence of Intergranular Brittle Fracture. It is important to remember, however, that there are other failures that will also exhibit evidence of Intergranular Brittle Fracture. Therefore, hydrogen embrittlement cannot be attributed to every part that fails in an Intergranular Brittle fashion. Unfortunately, I have seen far too many intelligent individuals jump to this conclusion without considering other options because common misconception suggests that every Intergranular Brittle Fracture is hydrogen embrittlement. The final misconception and perhaps the most dangerous is that hydrogen embrittlement is exclusively caused by the supplier's failure to bake parts after a manufacturing process that exposes the part to free hydrogen. In fact, and as the Bay Bridge failure illustrates, parts may be exposed to hydrogen after being placed into service. In these cases, although it is important to understand the manufacturing process history of the part, it is equally important to understand that the presence or absence of a hydrogen relief bake is a red herring and is not responsible for the failure of parts from environmental exposure to hydrogen.

To explain this further, hydrogen embrittlement can be broken into two different categories; Internal Hydrogen Embrittlement (IHE) and External Hydrogen Embrittlement (EHE). These two distinct categories boil down to the source of the hydrogen. IHE is where the parts pick up hydrogen during the manufacturing process. This may occur in the steel making, electro cleaning, or plating processes. Of these, we consider plating and perhaps electro cleaning as the two likelier sources. Although there is absorption during the steel making process there is no barrier, such as developed during electroplating, to trap the hydrogen inside, and, thus, the hydrogen freely leaves. IHE is normally discovered shortly after the parts are put into service, and can occur anywhere from a couple of minutes to several days after installation. EHE's source of hydrogen is from the environment, usually the result of a localized corrosion activity or from a nearby cathodic protection mechanism (such as is commonly used in sub-sea oil drilling). In many instances, localized corrosion activity produces large quantities of hydrogen as a by-product of the resulting chemical reactions that are occurring. If the corrosion is in a confined space, much of this hydrogen may be absorbed. EHE failures often take long times to develop and may not occur until months or years after the parts are placed into service.

What is Needed for a Failure to Occur?

Unlike some failure mechanisms whose parameters for failure are difficult to foresee, hydrogen embrittlement has four clearly understood parameters which must align in the right way, concentration, or intensity to result in a failure. There are three parameters that must be present and of sufficient concentration or intensity to spawn a hydrogen embrittlement failure. These are presence of hydrogen, application of high tensile stress, and material susceptibility. Figure 1 illustrates when these three parameters are present and integrated together, there may be a subset of parts where all the conditions are right for the presence of hydrogen embrittlement. Decouple any one of these three parameters and the risk of hydrogen embrittlement either significantly reduces or is entirely eliminated.

The fourth parameter is time. Although this is not coupled into the combination of these three other causal factors, all hydrogen embrittlement failures come with a time delay. This is because the movement and embrittling nature of the hydrogen is a time dependent process.

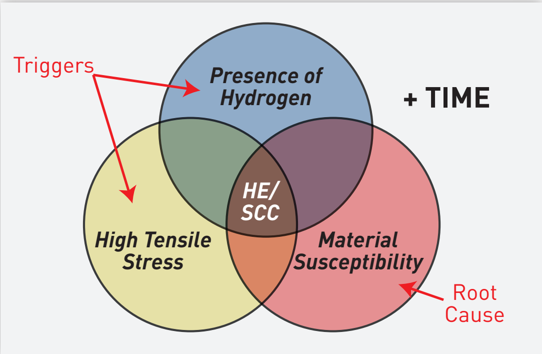


Figure 1: Required Parameters for a Hydrogen Embrittlement Failure

Of the three parameters needed for hydrogen embrittlement to occur, modern research suggests that the root cause always lies with the material susceptibility. In the fastener arena, the primary measure of material susceptibility is part hardness and newer research results suggest that the critical number appears to be Rockwell Hardness HRC39. Parts equal to and below this are not susceptible and parts above this number are susceptible. This means that, generally speaking, Property Class 10.9 and Grade 8 parts and below will be safe from hydrogen embrittlement.

These findings do challenge much of the traditional thought on the subject. There are many standards, both consensus and company specific which provide guidance that the critical hardness threshold is less than HRC39. In fact, several standards go as low at HRC32. Until the industry gets comfortable with the new findings and specifications become more uniform to one another, it is imperative that fastener suppliers continue to follow the guidance of specifications or other contractual instructions dictated by their customer. It is important to consider, as well, that although hardness is a primary or first order measure of material susceptibility, there are other material characteristics that may also play a role in susceptibility. These are considered second order and include characteristics such as toughness (measured by Charpy impact test), material "cleanness" (amount and size in inclusions), and microstructure homogeneity.

The other two parameters, presence of hydrogen and high tensile stress are considered triggers. In and of themselves, they are not the determining factor as to whether a part will fail by hydrogen embrittlement. However, if you take them out of the equation or reduce them below critical levels of concentration or intensity, they will fail to trigger even a susceptible part to failure.

Risk Prevention:

The best preventative measure is to decouple from the equation one of the parameters that leads to hydrogen embrittlement. In other words, keep part hardness below HRC39 and when utilizing large diameter product, verify uniform microstructure and good toughness. (Note: The failed Bay Bridge 4" diameter A354 anchor rods exhibited poor hardness uniformity and low toughness.) Attempt to limit or reduce tensile stresses. Utilize processes that do not expose parts to hydrogen and bake parts that need it for relief.

The traditional method of hydrogen relief in parts deemed "at risk" has been to bake them at a low temperature for a defined period of time. The idea behind baking is that the elevated temperature will excite the trapped hydrogen and cause it to leave the parts. The baking operation is normally done following plating or coating processes that expose parts to hydrogen. Although it would seem to be very simple, it can actually be quite costly depending on a vendor's capacity and ability to efficiently schedule parts in and out of the process in a timely manner.

Just as the critical hardness value to trigger a baking operation is not uniformly accepted, neither is the baking time. Every specification and industry seems to take a different position on this so that the standards seem to range from baking 4 hours to 24 (or more) hours at temperature. The traditional approach in automotive has been the "4-4-4" rule, baking four hours at 400°F within four hours of plating. Some standards have a slight twist on this and require baking within one hour of plating. The most recent research data suggests that four hours of baking is insufficient and that there is no evidence of beneficial effects of baking within a specified time limit, either one or four hours after plating.

One of the best measures of risk prevention is to conduct regular testing. Although some incidence of hydrogen embrittlement may be a very small percentage of the entire lot of parts, testing is simple to do and cheap insurance. Most standards provide guidance related to how a hydrogen embrittlement test is to be conducted. Like any other requirement, these should be followed as specified. Most tests will provide results in twenty-four to forty-eight hours.

Conclusion:

Hydrogen embrittlement is perhaps one of the most feared experiences that a fastener supplier or user will ever have to endure. Fortunately, there is good news. With a good understanding of what causes hydrogen embrittlement and the ways to prevent it, and then consistently and uniformly employing these practices, an organization should be able to prevent a hydrogen embrittlement failure. In the last couple of years, many thorough studies and experiments have been conducted on the topic and new information is being found. As more standards get updated to reflect these findings and organizations adopt the latest guidance, many entrenched in the old paradigms and practices will find the changes challenging. However, in the end, I foresee the industry will continue to move towards higher ground and strive to find new and better ways to prevent hydrogen embrittlement failures from occurring.

Further Study:

Anyone interested in further information on this topic should obtain a copy of "Fundamentals of Hydrogen Embrittlement in Steel Fasteners" by Salim Brahimi. Mr. Brahimi released this report in 2014 subject to research that he has spearheaded in partnership with his company IBECA Technologies Corp., McGill University in Montreal Canada, the Industrial Fasteners Institute, and a number of other academic and industry sponsors. A free copy can be obtained from the Industrial Fasteners Institute's website, www.indfast.org.