A Review on Failures of Industrial Components due to Hydrogen Embrittlement & Techniques for Damage Prevention

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Abstract

Hydrogen embrittlement is a well-known phenomenon in which a metal is weakened by the incorporation of hydrogen in or below its surface. Hydrogen embrittlement (HE) of steels is of great concern in many industries e.g. power, fuel, aerospace, automobile, transportation & other critical applications, where failure can have catastrophic consequences. This paper focuses on the failure aspect of industrial components on account of hydrogen embrittlement and prevention of such failures to avoid accidents thereby enhancing the system reliability and safety as an objective of maintenance strategy.

The prevention of HE is an important concern for designers, manufacturers and application engineers. This is particularly true with respect to the selection and application of materials, manufacturing process, application environment & service conditions. In course of describing the techniques for protection from HE, the various important aspects of hydrogen embrittlement e.g. failure characteristics, mechanism, identification, testing etc. have been discussed with a view to provide a complete insight of subject.

This paper presents a review of recent research emphasising to protect the equipments/ components from HE failure leading to enhancement in service life. The literature shows that despite much work has been done on hydrogen embrittlement, the scientist agree that much is still not understood and considerable discussion exists regarding the mechanisms. However, one thing is certain; hydrogen can cause catastrophic failure and need considerable focus to mitigate accidents and improve system reliability.

Keywords: Hydrogen embrittlement; Mechanism; Test methods; Susceptibility; Prevention techniques.

INTRODUCTION

Basics of Hydrogen Embrittlement

Hydrogen Embrittlement is the process by which metals such as steel become brittle and fracture due to the introduction and subsequent diffusion of hydrogen into the metal. This is often a result of accidental introduction of hydrogen during forming and finishing operations [1]. This phenomenon was first described in 1875 by Johnson [2].

Hydrogen Embrittlement results in decrease of toughness or ductility of a metal due to the presence of atomic hydrogen. During hydrogen embrittlement, hydrogen is introduced to the surface of a metal and individual hydrogen atoms diffuse through the metal. Because the solubility of hydrogen increases at higher temperatures, raising the temperature can increase the diffusion of hydrogen [3]. When assisted by a concentration gradient where there is significantly more hydrogen outside the metal than inside, hydrogen diffusion can occur even at lower temperatures. These individual hydrogen atoms within the metal gradually recombine to form hydrogen molecules, creating pressure from within the metal. This pressure can increase to levels where the metal has reduced ductility, toughness, and tensile strength, up to the point where it cracks open (hydrogen-induced cracking, or HIC).

Types of Hydrogen Embrittlement

Basically there are two types of hydrogen embrittlement; first one is the Internal Hydrogen Embrittlement (IHE). IHE is the hydrogen embrittlement which is caused due to the residual hydrogen emanated from processing and manufacturing methods, prevention of which is discussed later in this paper. Some processes giving arise to IHE are electroplating, acid pickling etc. [4].

The other form of hydrogen embrittlement that the engineers and scientists are encountered with is External Hydrogen Embrittlement (EHE). EHE pertains to the incursion of hydrogen from external sources like hydrogen rich environment. Stress corrosion cracking is an example of EHE [5].

Mechanism of Hydrogen Embrittlement :

Hydrogen embrittlement is a very complicated process with many underlying mechanisms. Often, failure will result from a combination of several influences, making the determination of governing mechanism very difficult. To date, three main embrittlement mechanisms have been proposed: hydrogen-enhanced decohesion (HEDE), hydrogen-enhanced localized plasticity (HELP), and hydride-induced embrittlement (HIE) [6].

In the following sections, each mechanism has been discussed

Hydride-induced embrittlement (HIE) -

The stress-induced hydride formation and cleavage mechanism is one of the well-established hydrogen embrittlement mechanisms with extensive experimental and theoretical support. The nucleation and growth of an extensive hydride field ahead of a crack has been observed dynamically by Robertson et al. In α-Ti charged from the gas phase in-situ in a controlled environment transmission electron microscope. In their observations the hydrides first nucleated in the stress-field of the crack and grew to large sizes not by the growth of individual hydrides but by the nucleation and growth of new hydrides in the stress field of the others. They showed that these small hydrides grew together to form the larger hydrides. This auto-catalytic process of hydride nucleation and growth together with brittle nature of them seems to be the main cause of embrittlement of typical hydride former element, i.e. the element of the group Vb; e.g. V, Nb, Ti and Zr.

Hydrogen-enhanced de-cohesion (HEDE)-

The de-cohesion model is one of the oldest models used to represent the change of properties as a result of atom hydrogen. It was described first in 1941 by Zapffe and Sims. It is based on the increased solubility of hydrogen in a tensile strength field, for instance on the tip of a crack or in areas with internal tensile strength or in the tension field of edge dislocations .The increased solubility of hydrogen in this tension field results in a decrease in the atom binding forces of the metal lattice. The influence of stress results in a premature brittle-material fracture along the grain boundaries (inter-granular cleavage) or network levels (trans-granular cleavage) owing to the decrease of the binding forces.

Hydrogen-enhanced localized plasticity (HELP)-

The most recent process model by far is the so-called HELP (Hydrogen Enhanced Local Plasticity) process. A prerequisite for the HELP process is, as is the case with the de-cohesion model, the accumulation of hydrogen in the field of stress, for instance, in the vicinity of the tips of cracks or in the stress areas of dislocations (carriers of plastic deformation in a metal grid). During the initiation of a dislocation movement by introducing external stresses, the existing active hydrogen considerably eases the dislocation movement through shielding the fields of stress of the dislocations against each other as well as against other grid defects. Therefore, a local dislocation movement will already occur at low levels of shearing stress, which is caused by a local drop of yield stress due to hydrogen. A sliding localization occurs, leading to a micro crack caused by the formation of micro pores and shearing action. As soon as the crack leaves the area of reduced yield stress, it will not propagate any further.

FAILURE CASES DUE TO HYDROGEN EMBRITTLEMENT

Hydrogen embrittlement is an unpredictable phenomenon which comes across in almost every industrial branch of engineering like power-plant, chemical, gas processing, automobile, aerospace etc. Hydrogen embrittlement damages the components by reducing their ductility and strength, so it is difficult to predict the life of component.

Some of the critical component failure on account of Hydrogen embrittlement are discussed as follows :

Failures of high strength steel fasteners

High strength mechanical steel fasteners are broadly characterized by tensile strengths in the range of 1,000 – 2,000 MPa (150 – 300 ksi), and are often used in critical applications such as in bridges, vehicle engines, aircraft, where a fastener failure can have catastrophic consequences. **[7]**When high strength steel is tensile stressed, as is the case with a high strength fastener that is under tensile load from tightening, the stress causes atomic hydrogen within the steel to diffuse (move) to the location of *greatest stress* (e.g., at the first engaged thread or at the fillet radius under the head of a bolt). As increasingly higher concentrations of hydrogen collect at this location, steel that is normally ductile gradually becomes brittle. Eventually, the concentration of stress and hydrogen in one location causes a hydrogen induced (brittle) micro crack. The brittle micro crack continues to grow as hydrogen moves to follow the tip of the progressing crack, until the fastener is overloaded and finally ruptures.

Figure 1. Typical Fastener Failure by Hydrogen Embrittlement [8]

In 2013, six months prior to opening, the East Span of the Oakland Bay Bridge failed during testing. Catastrophic failures occurred in shear bolts in the span, after only two weeks of service, with the failure attributed to embrittlement, possibly from the environment.

Failure of High pressure hydrogen storage tanks

Currently, austenitic stainless steel AISI 316 (SS 316) is the predominant material of construction for high-pressure hydrogen components and tubing, and has recently been incorporated into the construction of high-pressure hydrogen storage tank liners. A type- III storage tank consists of a metallic liner fully wrapped in glass or carbon fibres1. The main function of the fibre is to provide the strength required to contain the pressure. Tanks with higher storage pressure capacity will typically use a carbon fibre wrap because glass fibres can be susceptible to stress corrosion cracking. The principal function of the liner is to prevent escape of the gas, although it would also offer /contribution to the overall strength. On average, metallic liner materials are expected to sustain about 20% of the load imparted during pressurization1. It is important for the liner material to have low permeability of hydrogen for containment of the gas, high toughness for impact resistance, and resistance to corrosion and hydrogen embrittlement, The research result most relative to the field of material testing and certification for use in the hydrogen industry is that hydrogen environment embrittlement is dominant at the material surface. Once a crack forms, a constant supply of hydrogen to its tip will facilitate propagation via the de-cohesion model of hydrogen embrittlement.[6]

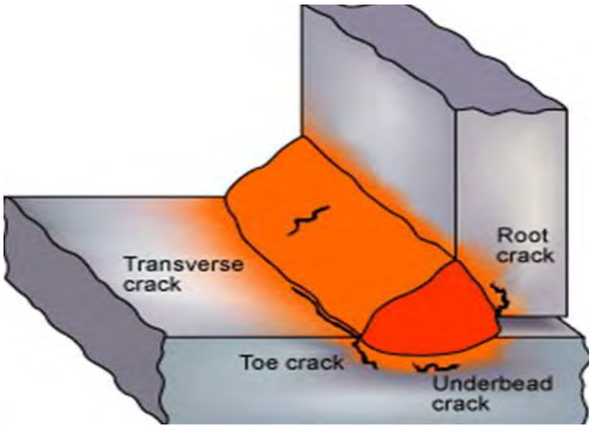
Figure 2. High Pressure Hydrogen storage tank [6]

A first example is the failure of a storage tank for compressed hydrogen. The consequences of this can be ascertained from Fig. 1. This failure was caused by the growth of large fatigue cracks which was induced by hydrogen insurance. The total damage paid by insurance in this case was approximately US$50 million. Hydrogen damage is more frequent than many people would suspect.

In the minds of people, hydrogen is often synonymous with danger especially since the Hindenburg disaster on 6 May 1937. On that day, the Zeppelin inflated with 200,000 m^3 of H_2 ignited in less than a minute resulting in the death of 35 out of the 97 passengers who jumped out of the airship out of panic. Even though the origin of the ignition is unknown, the combined combustion of hydrogen and the coating of the shell (butyrate, iron and aluminum oxide) is the cause. This caused such a fear of hydrogen called the "Hindenburg syndrome" that ever since the gas supply to the town from coking plant made up of 96 % H2 was called "water gas" to avoid any commercial repercussions.

Hydrogen induced cold cracking (HICC) in a low alloy steel weldments

In high strength steel weldments, hydrogen is introduced by the arc of welding and diffuses to the heat affected zone where susceptible microstructures such as martensite and bainte are present. This causes hydrogen embrittlement. At critical residual stress, the Hydrogen Induced Cold Cracking (HICC) occurs. Thus, HICC occurs due to three factors: i) a susceptible microstructure; ii) sufficiently high concentration of diffusible hydrogen and; iii) a critical stress intensity.



(a)

(b)

Figure 3 (a,b). Failure of weldment [9]

[9] Hydrogen cracking may also be called cold/ delayed cracking. During the welding process, hydrogen is introduced to the weld metal from the moisture or other hydrogenous compounds in the electrode, the covering flux, atmosphere and the weld material. A part of hydrogen diffuses out of weldments during the solidification, another part is trapped in hydrogen traps such as dislocations, grain boundaries, inclusions etc, and the third part diffuses to the Heat Affected Zone (HAZ). This causes Hydrogen Embrittlement (HE) of HAZ microstructure. In low alloy steels, fast cooling rate in the HAZ usually generates hard

microstructures such as martensite, bainite which are extremely susceptible to HE. Thus, HICC occurs in the HAZ under local residual stress or restraint stress.[10]

We can identify HICC by several features:

1. It occurs in a delayed manner from several seconds to several days after the welding;
2. Temperature less than 200°C;
3. Hydrogen and a susceptible microstructure are both present at the crack tip.

Failure of aircraft components due to hydrogen embrittlement:

A bolt from an aircraft flap control unit fractured in the threaded region of the shank near the shoulder with the head upon installation after a major service. A metallurgical investigation was carried out to identify the cause of failure. The bolt was manufactured from cadmium-plated, high-strength steel. Material checks carried out on the bolt showed that it conformed to the required specification and was found to have an approximate ultimate tensile strength of 1380 MPa.

The fracture surface of the failed bolt was examined using SEM to identify the mode of fracture and determine if pre-existing defects were present that could account for the unexpected failure. The fracture surface exhibited two distinct modes of failure. The center of the bolt exhibited ductile features, while the outer circumference exhibited inter-granular features. Both modes of crack growth were caused by static overload failure, but the ductile appearance at the center should have been present throughout. The inter-granular region around the outer edge was suggestive of embrittlement, which had led to premature failure at loads below those anticipated. The embrittlement in this case was attributed to the cadmium plating, which is applied to the bolts to provide corrosion protection to the steel. Hydrogen is evolved during the plating process, which becomes absorbed by the steel. The cadmium plating acts as a barrier to hydrogen diffusion at ambient temperature so that the hydrogen becomes 'trapped' in the steel. In high strength steels (>1100 MPa) this leads to embrittlement. To overcome this problem, high strength steel fasteners, which have been cadmium-plated, are baked at 175-205°C for 24 hours to allow hydrogen to diffuse through the cadmium. In this case, failure of the bolts was caused by insufficient baking after plating, which gave rise to hydrogen embrittlement. [11]

COMMON CHARACTERISTICS OF HE FAILURE

- HE phenomenon occurs with high strength steel components.
- Components subjected to protective coatings e.g. Zinc electroplating are more sensitive for HE damage.
- Parts in contact with acid during manufacturing or service may subject to HE failure.
- If the failures are due to IHE it must have occurred just after some time of installation, usually one hour to one day.
- The fasteners hardened to at least Rockwell C37 may subject to HE failures. Unhardened fasteners never suffer from hydrogen embrittlement. [8]
- The appearance must be that of an "inter-granular" failure. Look closely at the surface of the broken areas in the photograph in this article. The surface of the failure looks relatively smooth with a texture that looks like the surface of emery cloth. If you look at it under magnification, you see that the surface has a crystalline appearance with many sharp faces or facets. [8]

FACTORS THAT INFLUENCE HYDROGEN EMBRITTLEMENT ON PARTS [8]

The severity and mode of the hydrogen damage depends on:

- Source of hydrogen—external (gaseous)/internal (dissolved).
- Exposure time.
- Temperature and pressure.
- Presence of solutions or solvents that may undergo some reaction with metals (e.g., acidic solutions).
- Type of alloy and its production method.
- Amount of discontinuities in the metal.
- Treatment of exposed surfaces (barrier layers, e.g., oxide layers as hydrogen permeation barrier on metals).
- Final treatment of the metal surface (e.g., galvanic nickel plating).
- Method of heat treatment. Level of residual and applied stresses.

Hydrogen embrittlement is a common, dangerous, and poorly understood cause of failure in many metal alloys. In practice, it is observed that different types of damage to industrial components have been tied to the presence and localization of hydrogen in metals. Many efforts have been made at understanding the effects of hydrogen on materials, resulting in an abundance of theoretical models and papers. However, a fully developed and practically-applicable predictive physical model still does not exist industrially for predicting and preventing hydrogen embrittlement[18].