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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]

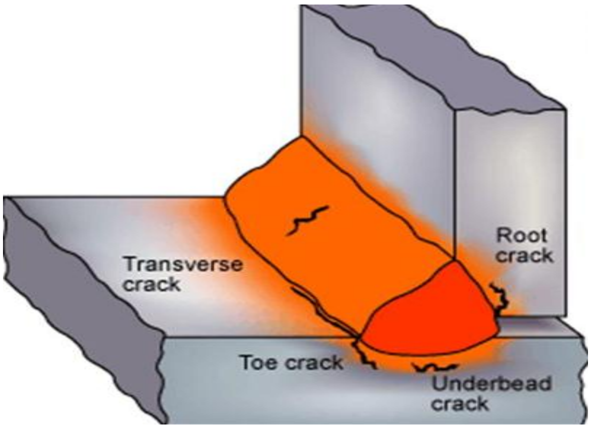
Figure 2. High Pressure Hydrogen storage tank [6]

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.



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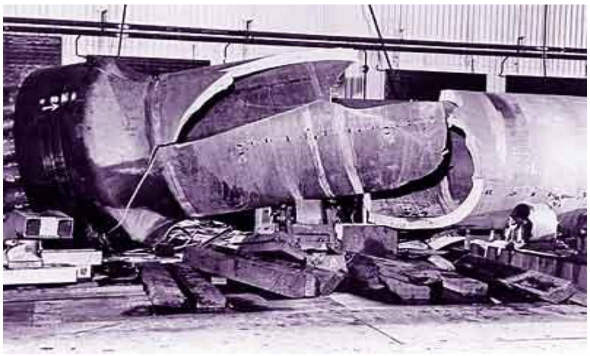


(b)

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].

MATERIAL SUSCEPTIBILITY TO HYDROGEN EMBRITTLEMENT

Hydrogen atoms embrittle a variety of substances, including steel, aluminium(at high temperatures only)and titanium. Hydrogen embrittlement of high-strength steel is of the most importance. Austempered iron is also susceptible, though austempered steel (and possibly other austempered metals) display increased resistance to hydrogen embrittlement. Steel with an ultimate tensile strength of less than 1000 MPa (~145,000 psi) or hardness of less than 30 HRC is not generally considered susceptible to hydrogen embrittlement. In tensile tests carried out on several structural metals under high-pressure molecular hydrogen environment, it has been shown that austenitic stainless steels, aluminium (including alloys), copper (including alloys, e.g. beryllium copper) are not susceptible to hydrogen embrittlement along with a few other metals. As an example of severe hydrogen embrittlement, the elongation at failure of 17-4PH precipitation hardened stainless steel was measured to drop from 17% to only 1.7% when smooth specimens were exposed to high-pressure hydrogen.

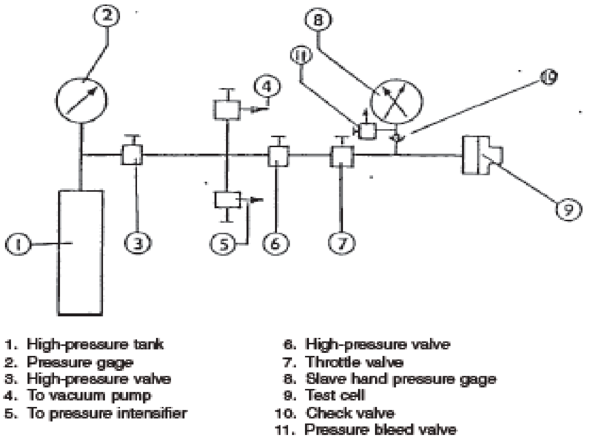
Hydrogen embrittlement can occur during various manufacturing operations or operational use - anywhere that the metal comes into contact with atomic or molecular hydrogen. Processes that can lead to this include cathodic protection, phosphating, pickling, and electroplating [17]. A special case is arc welding, in which the hydrogen is released from moisture, such as in the coating of welding electrodes. To minimize this, special low-hydrogen electrodes are used for welding high-strength steels. Other mechanisms of introduction of hydrogen into metal are galvanic corrosion, as well as chemical reactions with acids or other chemicals. One of these chemical reactions involves hydrogen sulphide in sulphide stress cracking (SSC), an important process for the oil and gas industries.

TEST METHODS/ TECHNIQUES FOR IDENTIFICATION

Disk Pressure (rupture) test

ASTM F1459, "Standard Test Method for Determination of the Susceptibility of Metallic Materials to Gaseous Hydrogen Embrittlement" is suggested for use in selection of metallic materials "for applications in which hydrogen in any form (liquid, gaseous, mono atomic, etc.) produced by corrosion, electrolysis, chemical process, etc. is present" [20]. The method provides quantitative information on hydrogen embrittlement susceptibility of metallic materials. Materials to be investigated are manufactured into thin disks of specified size. Disk-shaped specimens are subjected to increasing gas pressure until they burst. Some of the samples are tested in helium (control) gas and some in hydrogen gas. Three sets of two specimens with identical dimensions and temper conditions are burst for each test. If the burst pressures of disks exposed to hydrogen and helium are essentially the same, it is concluded the material is not susceptible to hydrogen embrittlement. If the ratio of helium to hydrogen burst pressure is two or greater, the material is considered susceptible to hydrogen. The benefits of this test method include its simplicity and quantitative results. A limitation is that the specimen geometry is disk-shape only. In addition, the actual test may be fast, but set-up for the test is somewhat complex and time consuming.

The test method requires a machined test cell, specimens, high pressure helium and hydrogen gases, valves, pressure gages, tubing, and a vacuum pump as shown in Fig 4(a) and (b).



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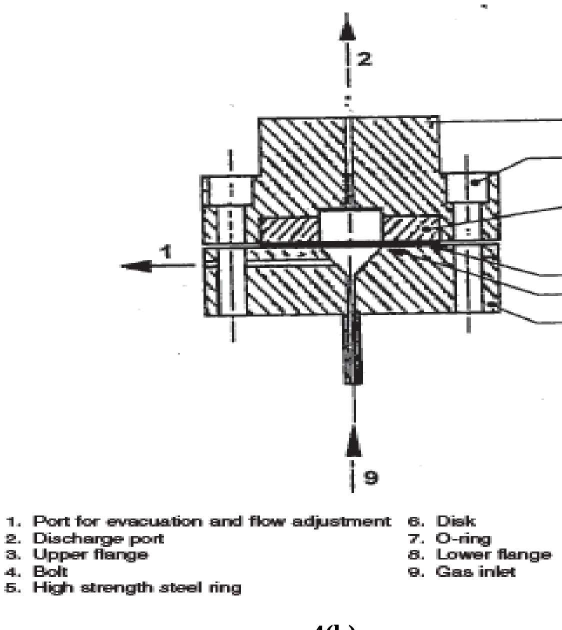

4(b)

Figure 4.(a) Schematic of disk pressure test;
(b) Test cell. [20]

Constant load test

Constant load tests for susceptibility of materials to hydrogen embrittlement are described in BS EN 2832 [14] and ASTM F519 [12]. The two methods are essentially the same, their main difference being the level of applied load: specimens are exposed to less stress in BS EN 2832 than in

ASTM F519. BS EN 2832, "Hydrogen Embrittlement of Steels – Notched Specimen Test" describes a constant load test for assessing hydrogen embrittlement in steels residual from electrolytic or chemical surface treatments. Specimens are subjected to an axial load equal to 75% (+/- 2%) of the tensile strength of a notched, uncoated specimen, for a period of 200 hours. Notched specimen dimensions and tolerances are provided in the standard. The material and heat treatment must be identical with those of the parts. Surface treatment must be carried out on the specimens as on the parts, and the thickness of any applied surface deposit must be the same at the notch root as that specified for the part surface. The experiment is performed in air. A valid test requires that fracture not occur within the 200 hour test span. Notched test specimens and a device for delivering constant load are required for the test. ASTM F519, "Standard Test Method for Mechanical Hydrogen embrittlement Evaluation of Plating Processes and Service Environments" employs a notched round bar tension test under constant load, Type l a; see Figure 4

Specimens are subjected to the sustained load test (SLT). Plated specimens are tested in air, and service environments may be applied around the specimen during the test. The test is pass/fail based on a sustained load of 75% of the fracture stress of the specimen (note: not yield stress) maintained for 200hours. Specimens and a load machine with sufficient load capacity are required for these tests. ASTM F519 tests were designed for process control of hydrogen produced by different plating processes and as a result of exposure to different chemicals encountered in service environments. The method assumes that air melted AISI 4340steel per MIL-S-5000 at 51 to 53 HRC is the worst case; that is, all other heat treated, high-hardness steels are less susceptible to hydrogen embrittlement. It may be feasible, however, to adapt these tests to evaluate other alloys and/or exposures. The clearest benefits of the constant load tensile test are that the stress condition of the specimen is well-defined, and the test is relatively easy to perform. Stress is calculated from load divided by the initial cross-section (transverse) of the specimen. Once cracking occurs, it is likely to progress, because the specimen stress rises with decreasing remaining cross-section under constant load. The pass/fail criterion is therefore easily verified. A limitation of this test method is the required specimen geometry, which rarely allows complex shapes or actual manufactured parts. Also, seals to a hydrogen containing environment may be prone to leaking.

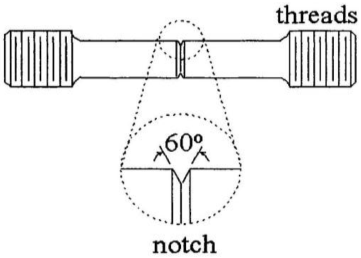

Figure 5. Type 1a specimen geometry (ASTM F519) [12]

Inclined Wedge test

Threaded items may be tested for hydrogen embrittlement using ASTM B839, "Standard Test Method for Residual Embrittlement in Metallic Coated, Externally Threaded Articles, Fasteners, and Rod-Inclined Wedge Method." [18] The test method has two main functions: 1) it may be used in the statistical-basis determination of batch lot rejection or acceptance, and 2) it may be used to determine the effectiveness of processing steps (i.e., pre- and post-baking treatments) in reducing mobile hydrogen in threaded metallic items. Not to be confused with the wedge-opening load test, which involves constant wedge or crack opening displacement, ASTM B839 describes a test for threaded objects in which the object is inserted into a wedge of specified angle and joined to a mating nut on the opposite side; see Figure 6.

Testing is carried out after performing hydrogen embrittlement relief heat treatment. Selection of samples should be performed in accordance with the required quality assurance level. A minimum sample size of 30 pieces is necessary from each embrittlement relief treated batch that exceeds 500 pieces of plate as a single group. For other cases, a minimum of five items from the test lot is selected at random and tested. The nut is tightened until a load equal to 75% of the ultimate tensile strength of the item is induced.

After the prescribed tensioning is applied, a specified period of time is allowed to lapse, after which tension is re-measured and the parts are examined for failures such as cracks, separated heads, and breakage (embrittlement failure), while the parts are still mounted in the wedge. Following this examination, the torque is re-measured, and torque relaxation greater than 10% is recorded as failure. Finally, the nuts are removed and the parts are examined for failure from transverse cracks. This test method has been coordinated with ISO-DIS10587 and is technically equivalent.

A major benefit of this test method is its applicability to threaded articles, fasteners, and rod made from steel with > 1000 MPa (145 psi) tensile strength (with corresponding hardness values of 300 HVI0 kgf,303 HBN, or 31 HR or surface hardened threaded articles, fasteners or rod. A limitation is that the applied torque is a calculated value, so that the "75% of ultimate tensile strength" must be estimated by calculation or calibration from untreated parts [3]. Also, the initial inspection may be difficult, because the presence of cracks may only become apparent after removing the part from the wedge. The test method requires a hardened wedge, filler plate(s), a hardened washer, and a method for applying and measuring load (i.e., torque application device).

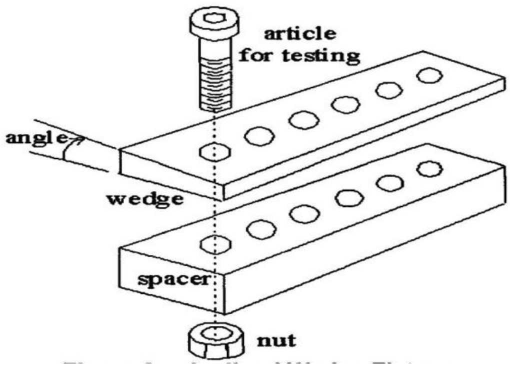

Figure 6. Inclined Wedge Fixture (ASTM B839) [18]

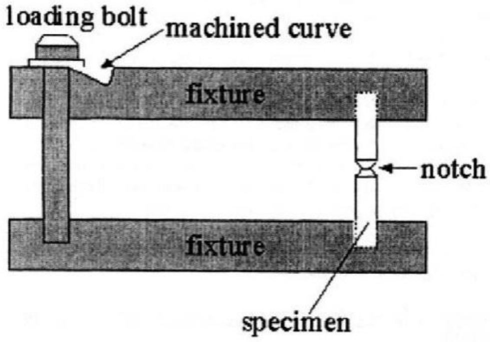

Figure 7. (a) Notched round bar (After ASTM F519)

Four-point bend test

Four-point bend tests contained in ASTM F519 [12] and ASTM F1624 [12] were reviewed. ASTM F519 describes two types of four-point bending specimens and loading methods: Type l c notched round bar specimens are tested using a self-loading fixture; see Figure 7(a). Type le notched square bar specimens are tested using appropriate four-point bend adapters under displacement control; see Figure 7(b). An important benefit of these self-loading fixtures is that the assemblies may be inserted into closed test vessels and exposed to environments without interruption.

In Type l c notched round bar testing, four-point bending is applied using a self-loading fixture. The device is calibrated by counting the number of loading bolt turns required to fracture anon-exposed specimen of air melted AISI 4340 steel. Stress levels for exposed specimens are then indicated as a percentage of the average number of turns necessary to cause fracture during calibration.

Because of the shape of the loading fixture, the applied load on the specimen is essentially constant. In Type 1e notched square bar testing, four-point bending is applied using the sustained load test (SLT technique per ASTM F519) or the rising step load test (RSL technique per ASTM F1624).

Prior to the test, notched square bars are heat treated and machined to specific tolerances. The loading protocol (hold time and step load value) is detailed in the standard. Since the threshold is measured with the RSL test method, equivalent loads are related to the percentage of the fracture strength. Therefore, to meet the requirements of the SLT, only the specified percentage of the fracture strength needs to be attained with the RSL test. This allows for equivalent interpretation of the SLT and RSL test methods.

The results are interpreted as follows:

1) For test specimens that exceed 90% of their RSL fracture strength the plating bath is considered to be non-embrittling.
2) For test specimens that exceed 75% of their RSL fracture strength, the plating bath is considered to be of acceptable quality.

METHODS/ TECHNIQUES FOR PREVENTION OF HYDROGEN EMBRITTLEMENT

Steps that can be taken to avoid hydrogen embrittlement include reducing hydrogen exposure and susceptibility, baking after plating (mandatory and as soon as practical) and using test methods to determine if a material is suspect. Other options that could help in avoiding hydrogen embrittlement include the use of lower strength steels (not always viable), the avoidance of acid cleaning, the utilization of low hydrogen plating techniques and the reduction of residual and applied stress [7].

- Reducing Corrosion Rate- Hydrogen embrittlement occurs frequently during pickling

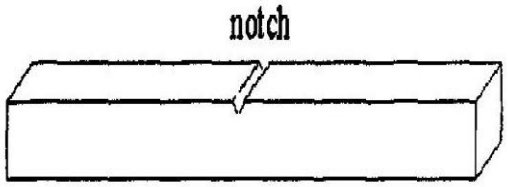

Figure7.(b) Specimen geometry (ASTM F519) *[5]*

- Operations where corrosion of the base metal produces vigorous hydrogen evolution. By careful inhibitor additions, base-metal corrosion can largely be eliminated during pickling with a subsequent decrease in hydrogen pickup.
- Using Clean Steel- Rimmed steels tend to have numerous voids, and the substitution of killed steel greatly increases the resistance to hydrogen interstitials for embrittlement because of the less number of voids in this material [21].
- Baking- Hydrogen embrittlement is an almost reversible process, especially in steels. That is, if the hydrogen is removed, the mechanical properties of the treated material are only slightly different from those of hydrogen-free steel. A common way of removing hydrogen in steels is by baking at relatively low temperatures at 200-300 F [22].

- Practicing Proper Welding- Low hydrogen welding rods should be specified for welding if hydrogen embrittlement is a problem. Also, it is important to maintain dry conditions during welding since water and water vapour are major sources of hydrogen.
- Substituting Alloys- The materials most susceptible to hydrogen embrittlement are the very high-strength steels. Alloying with Ni or Mo reduces susceptibility. Because, Nickel-containing steels and Nickel-base alloys have very low hydrogen diffusion rates and best way to prevent from hydrogen embrittlement [23].
- Protective coatings : A plethora of coatings exist that have been demonstrated to reduce either the outgassing of hydrogen in vacuum systems, or as diffusion barriers to the ingress of hydrogen. The most modern non structured coatings e.g. graphene, Tic, Tin, Al_2O_3 are still need to be proved for enhanced service life and barrier for hydrogen embrittlement.

CONCLUSION AND PERSPECTIVE

We have discussed basic mechanism of hydrogen embrittlement along with its characteristics and factors affecting the development and behaviour of HE in specific service conditions. Also efforts are made to describe the various methods and techniques available to evaluate the effect of HE on high strength steels. Techniques for prevention of HE are also enlisted briefly. The discussion emphasise that research conducted are multidirectional and future efforts are to be made to develop economical and commercially means available to combat the hydrogen embrittlement.

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