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INTERNATIONAL ADVANCED RESEARCHES
and
ENGINEERING JOURNAL

Journal homepage: www.dergipark.org.tr/en/pub/iarej

e-ISSN: 2618-575X

International Open Access

Volume 08
Issue 02

August, 2024

*Review Article*

# A Review on hydrogen embrittlement behavior of steel structures and measurement methods

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ARTICLE INFO

*Article history:*
Received 03 January 2024
Accepted 04 July 2024
Published 20 August 2024

*Keywords:*
Brittle Fracture
Catastrophic Failures
High-Strength Steels
Hydrogen Embrittlement

ABSTRACT

Hydrogen can be found within metals under a variety of industrial and environmental conditions. Hydrogen-metal interactions can take place through hydrogen embrittlement, hydrogen sulfide corrosion, or hydrogen absorption. Steel and other metals that are exposed to hydrogen may experience a difficulty known as hydrogen embrittlement that affects their mechanical properties. The material's ductility and toughness may be reduced as a result of this phenomena, it also increasing the risk of brittle fracture. In steel, atomic hydrogen mainly diffuses into the microstructure of the steel, causing hydrogen embrittlement. Localized weakening of the bonds between the metal atoms might result from hydrogen atoms occupying interstitial positions in the metal lattice. Especially when under stress, this may lead to a more susceptible to fracture and cracking. Concerns with hydrogen embrittlement arise in sectors like aerospace and oil and gas that use high-strength steels. If not appropriately handled, it may result in catastrophic failures. Use of hydrogen-resistant alloys, appropriate heat treatments, and protection from conditions that promote hydrogen uptake are examples of preventive measures. This literature review paper covers the definition of hydrogen embrittlement (HE), mechanisms causing HE, measurement of hydrogen concentration and preventive measures that restrict hydrogen diffusion to the steel.

## 1. Introduction

Hydrogen gas is usually trapped in metal by a number of ways. These result from hydrogen embrittlement, interstitial diffusion [1], chemical reaction, and absorption. Hydrogen atoms can become trapped in high-stress areas of the metal structure, including grain boundaries or fracture tips, in the event of hydrogen embrittlement [2]. Even at lower stress levels than those that would typically cause fracture in the absence of hydrogen, the buildup of hydrogen at these locations can cause localized embrittlement and encourage the spread of cracks [3]. A number of variables, including the metal's crystal structure, hydrogen solubility, diffusion kinetics, and the specific environmental circumstances in which the metal is exposed to hydrogen, affect the exact mechanism of hydrogen trapping [4]. A phenomenon known as hydrogen embrittlement, in which hydrogen gases become trapped on the inside of the liquid metal during the solidification process and penetrate the base material, can cause steel to become brittle. This can lead to a loss of ductility and toughness, making the material more susceptible to brittle fracture, even under relatively low stress conditions [5]. Fossil fuels could eventually be replaced with hydrogen, which reducing the environmental impact. However, hydrogen absorbs and permeates through metals, equipment exposed to hydrogen is susceptible to harmful consequences [6]. ASTM F2078 defines HE as "a permanent loss of ductility in a metal or alloy caused by hydrogen in combination with stress, either internal residual stress or stress applied externally." [7].

As hydrogen builds up in the crystal lattice and generates stress, Figure 1 illustrates the initial effect of hydrogen interaction, which is the development of HE [5].

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DOI: 10.35860/iarej.1414085

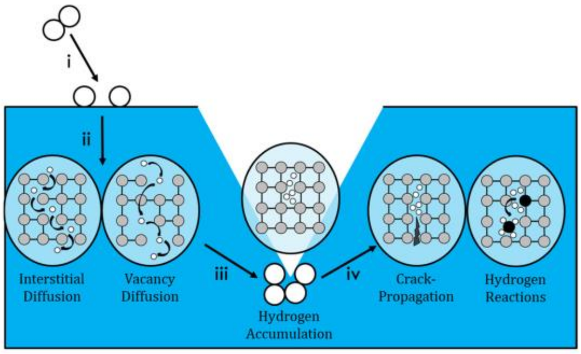


Figure 1 Diagrammatic representation of the interactions between hydrogen atoms and a metal crystal structure [5].

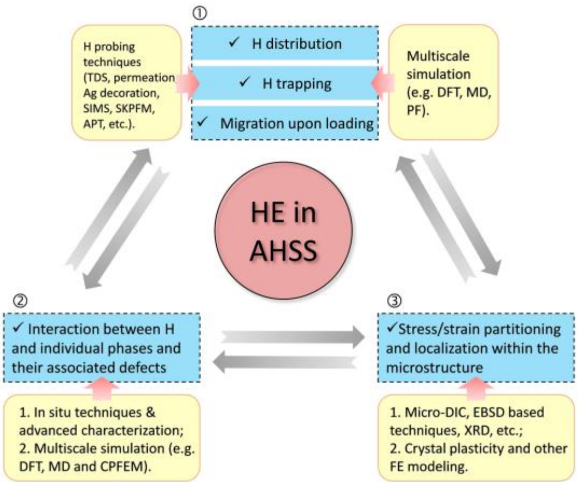


Figure 2. Hydrogen interaction and HE in AHSS [11]

The second effect is called a hydrogen attack and is caused by hydrogen building up in the crystal lattice, which reacts and interacts with other crystal lattice components to alter the stress and composition. Hydrogen has several advantages, such the possibility of being clean and renewable, but there are also major safety concerns. Not only is hydrogen flammable [8] and explosive, but it can also penetrate and erode metallic surfaces especially from high strength steels surfaces, which is a serious safety concern when handling and storing hydrogen [9]. The majority of metals and alloys have the capacity to absorb hydrogen, and its build-up near internal defects (such as vacancies, grain boundaries, dislocations, precipitates, and inclusions) poses a significant risk to iron, steel, nickel and titanium-based alloys, and numerous other materials that are typically used in industrial settings [6].

### 1.1 Interaction Between H and AHSS

Following loading distribution, trapping, and migration; the little H atoms' ability to interact with practically all metal flaws is well known. Because of this, its local distribution, atomic entrapment, and migration upon loading are essential for the activation of particular HE processes and, consequently, the local and global HE resistance. A lot more when it comes to AHSS than single-phase model alloys. Both in its non-distorted and deformed stages, complex microstructure often consists of many phases and lattice faults of various sorts [10]. Furthermore, the local thermodynamics and kinetics of H migration and redistribution are significantly impacted by the very complex evolution of microstructure, local stress states, and defects that is caused by deformation.

Within AHSS, there are typically significant differences across phases with regard to mechanical properties, the evolution of defects under load, H solubility, and difusivity. Different HE mechanisms are triggered by such fundamental differences, which in turn cause different H interactions with different phases. Both H trapping and migration as well as the local mechanical driving force for damage creation would be significantly changed by the local strain/stress states and how they evolved upon deformation [12].

Over the years, a great deal of research has been done on the hydrogen-induced degradation of metals; yet, hydrogen embrittlement, remains the cause of many industrial failures and the consequent catastrophic releases of dangerous compounds into the environment [13]. The aim of this review paper is to summarize the recently published papers specifically on the definition of HE, the events that lead to HE, the method for charging hydrogen, the technique for measuring hydrogen concentration, and the safety measures that limit the passage of hydrogen to steel.

## 2. Hydrogen Embrittlement in Steel

For advanced high strength steels (AHSS), hydrogen embrittlement becomes more significant when strength levels rise above 1000 MPa [6]. AHSSs have favorable mechanical properties, but hydrogen-induced processes have the potential to compromise their integrity [7]. When exposed to hydrogen, these materials lose some of their ductility and eventually experience HE [1-5]. This limitation could arise from exposure to the service environment, during the manufacturing process, during product assembly and termination, or both. The risk of hydrogen embrittlement can be raised by a number of variables the most common of them are shown in Figure 3.

Environmental Factors: The creation of hydrogen is facilitated by corrosive environments, which raises the possibility of embrittlement. Hydrogen production during corrosion processes can be accelerated in acidic environments (Silva et al., 2021). Although cathodic protection systems are useful in preventing corrosion, they may cause embrittlement by introducing hydrogen onto the metal surface. And also at higher temperatures, hydrogen embrittlement often reveals itself more strongly.

But it can also happen at room temperature, particularly with some materials [2].

Material Susceptibility: High strength materials, like certain alloys and high-strength steels, are more prone to hydrogen embrittlement [8]. The alloy's susceptibility to hydrogen embrittlement may vary depending on its composition. Certain alloying materials may reduce or increase the effects. Compared to other microstructures, steels with martensitic microstructures are more vulnerable to hydrogen embrittlement [9]. Embrittlement may result from hydrogen present at grain boundaries. Some microstructures might be more vulnerable than others, such as those with finer grains. Hydrogen can be introduced into the material through heat treatment and welding procedures [15]. Attentive regulation of these procedures is necessary to reduce the possibility of embrittlement.

Load (Stress): High levels of tensile stresses can make a material more vulnerable to hydrogen embrittlement [16]. This is especially relevant when materials are being mechanically loaded during manufacturing or during use [3]. Figure 3 shows a graphic representation of the key parameters for HE. Environmentally assisted cracking (EAC) can be observed with either a static or dynamic applied load, and the damage form is known by several names such as corrosion fatigue, stress corrosion cracking, sulfide stress cracking, and so on. One or more harm mechanisms (which may work concurrently) have the ability to initiate and/or assist each of the aforementioned damage kinds.

It is notable that the degree of hydrogen embrittlement varies depending on the material and application and is dependent on the interaction of these factors [17]. The implementation of preventive measures in corrosive settings, control over processing conditions, and suitable material selection are examples of prevention and mitigation strategies [10].

The development of successive generations of AHSS has resulted in a considerable improvement in the characteristics of steel during the past few decades [18]. Given their increasing usage in automobiles, these materials are especially intriguing to the transportation sector, such as the automotive industry, which is looking to minimize weight and consumption. However, because of their susceptibility to cracking, especially when hydrogen is present and causes HE, the potential of these novel steels is not being fully utilized. The local diffusible hydrogen content is the crucial parameter that determines the HE, which also depends on the steel's ability to trap hydrogen in an irreversible or reversible manner [11].

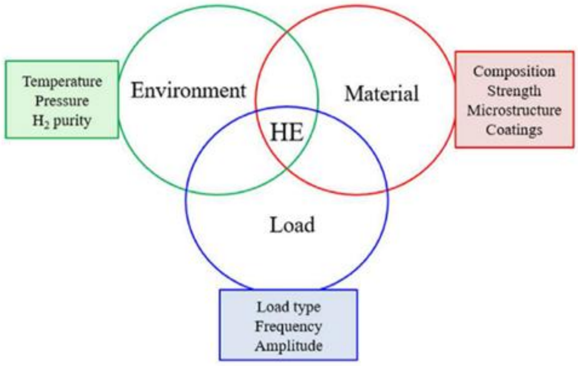


Figure 3. Factors that increase the risk of hydrogen embrittlement [3]

## 3. Mechanisms Causing HE

Complex processes that vary based on the particular material and ambient circumstances are responsible for hydrogen embrittlement. A few of the main mechanisms involved are as follows:

Adsorption-Induced Dislocation Emission (AIDE), Stress-Induced Hydrogen Embrittlement, Hydrogen-Enhanced Strain Localization, Hydride-Induced Embrittlement (HIE), Hydrogen-Enhanced Decohesion Mechanism (HEDE), Hydrogen-Enhanced Local Plasticity Model (HELP), and Hydrogen Changed Micro-fracture Mode (HAM) [9-12].

### *3.1 Hydrogen Enhanced Decohesion (HEDE)*

According to the HEDE mechanism, hydrogen weakens an alloy's cohesive strength [19]. Pfeil [20] first suggested the decohesion process in 1926, stating that "The cohesiveness between grain boundaries and cubic cleavage planes was reduced by hydrogen." A more refined version suggested that the cohesive strength of lattice planes or interface boundaries is decreased in the presence of hydrogen [21]. The underlying mechanism of HEDE is that an electron from a hydrogen atom dissolved in steel enters the unfilled three-dimensional shell of an atom (such as a Fe atom) that constitutes the steel. The interatomic repulsive forces are increased by these additional electrons in the d-shell, lowering cohesive strength. [12].

Figure 4 displays the HEDE mechanism schematic. The atomic bonds at the crack's tip weaken as a result of the crystal lattice expanding due to the admission of hydrogen. This leads to a reduction in the energy needed to facilitate the propagation of cracks, culminating in a macroscopic brittle fracture. Involving the tensile separation of atoms caused by the following: (i) hydrogen in the lattice; (ii) adsorbed hydrogen; and (iii) hydrogen at particle–matrix contacts, which weakens interatomic connections [12].

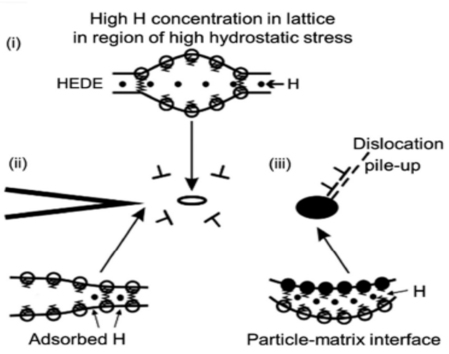


Figure 4. Schematic of the HEDE mechanism [12]

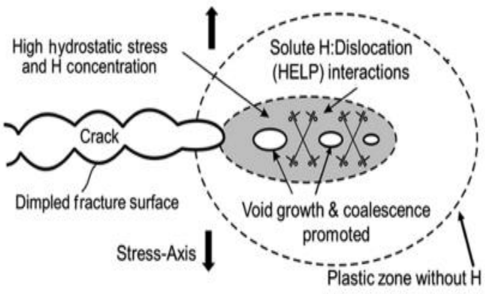


Figure 5. Schematic of the HELP mechanism [15]

### 3.2 Hydride-Induced Embrittlement (HIE)

This mechanism, which has strong experimental and theoretical backing, is one of the well-known mechanisms of HE. Hydrides originally formed in the crack's stress field, and they expanded to enormous sizes by forming new hydrides in the other hydrides' stress fields rather than by expanding from individual hydrides [14]. They demonstrated how the smaller hydrides developed into the larger hydrides through growth. Brittleness of the resulting hydride nucleation and development along with the auto-catalytic process appears to be the primary cause of embrittlement of the typical hydride former element [15].

### 3.3 Hydrogen Enhanced Localized Plasticity (HELP)

The hydrogen atom is accumulated in close to the crack tip. Moreover, it lessens the opposition to dislocation motion. As a result, dislocation becomes more maneuverable and functions in a metal lattice as a carrier of plastic deformation [22]. It might be clear that it depends on the material's microstructure, stress intensity, or hydrogen clustering. Fractographic examination was carried out to verify the material's microstructure characteristics. HELP contains a wide variety of structures, such as Face-Centered Cubic (FCC), Body-Centered Cubic (BCC), and Hexagonal Close-Packed (HCP) type structures. The HELP mechanism will cause a brittle fracture surface with tear ridges, dimples, and slip [15].

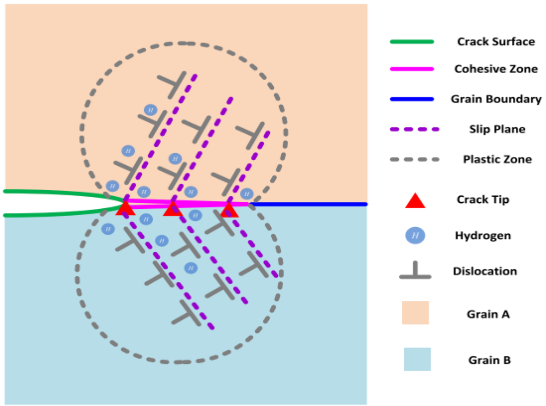


Figure 6. Diagrammatic representation of the hydrogen-induced dislocation emission from the crack tip in the AIDE mechanism model [9].

### 3.4 Adsorption Induced Dislocation Emission (AIDE)

This represents the combination of HEDE and HELP. Adsorption of the solute hydrogen atoms occurs close to the fracture tip. Because of the solute hydrogen atom dislocation that forms close to the fracture tip, hydrogen adsorption at the crack tip weakens the cohesive strength and interatomic bonding of materials via the HEDE process. Dislocation promotes the formation of micro voids through the HELP mechanism and the slip-induced crack development [21]. The process known as "adsorption-induce dislocation emission mechanism" occurs when hydrogen is adsorbed on a surface, which further enhances or inhibits the dislocation nucleation at the surface and has a significant impact on surface energy. In crystalline solids, dislocation nucleation, or emission from the fracture point, plays a crucial role in the ductile-brittle transition. A quantitative model was developed, as shown in figure 6, to capture the hydrogen-affected dislocation emission from the crack tip and its effect on hydrogen embrittlement. [23].

### 3.5 Hydrogen Assisted Micro-Fracture Mode (HAM)

Hydrogen causes a shift in the material's microfracture mode, causing the ductile to become brittle. Hydrogen charge decreased the material's ductility and caused the ultimate tensile strength fracture mode to shift from a cup-and-cone to a brittle shear fracture mode. This is also due to the shear fracture mode being amplified by the high concentration of hydrogen at the dislocation. HAM is the term used to describe the shift in micro fracture mode caused by the influence of hydrogen [5].

## 4. Measurement of Hydrogen Concentration in Steel

It's critical to measure the hydrogen concentration in steel, particularly in situations where hydrogen presence may compromise the integrity of the material. Hydrogen has a capacity to embrittle steel, which can alter its mechanical characteristics and perhaps result in structural failure [24]. Several well used techniques exist for determining the hydrogen content of steel. The development of the currently available AHSS, which reduce their vulnerability to HE in the presence of low hydrogen concentrations, requires precise monitoring of the concentration of hydrogen and trapping in the materials [25]. Methods for measuring concentrations and analyzing hydrogen trapping in metallic materials are: hydrogen microprint technique (HMT), thermal desorption spectroscopy (TDS), hydrogen permeation test (HPT), linearly increasing stress test (LIST) and gas chromatography (GC). The most widely used experimental methods for measuring concentrations and analyzing hydrogen trapping in metallic materials are now TDS and GC with thermal conductivity detectors (TCD) [26].

### *4.1 Hydrogen Microprint Technique (HMT)*

This technique has been used to calculate the hydrogen's diffusion through metal. Knowing these pathways allows for the identification of their unique microstructure and the determination of the hydrogen's effect. This high-resolution, very accurate HMT approach is relatively straightforward and distinct [27]. The hydrogen distribution on the stress field, for example in notched and deformed steel, was found using the HMT technique. The HMT process can be used on a variety of materials, including austenitic stainless steel, high strength steel, and low carbon steel [28]. During the procedure, a thin layer of AgBr gel is placed on the face of the hydrogen-charged substance. Hydrogen interacts with a silver salt as it breaks free of the metal. Following the reaction, silver ions take on a metallic form and leave an area where hydrogen contact occurred. The area has silver particles, and the extra unreacted gel is being removed from it. The sample is examined using a scanning electron microscopy (SEM), and when the sample is examined, hydrogen exits the areas where silver is present [29].

### *4.2 Thermal Desorption Spectroscopy (TDS)*

Certain features of the TDS spectra are associated with hydrogen trapping at dislocations, vacancies, vacancy complexes, grain boundaries, and interfaces of non-metallic inclusions (NMI), which enables the measurement of the hydrogen trapping activation energies. The TDS technique measures the amount of desorbed hydrogen by employing a limited and controlled heating procedure. There are traps in steel, and it's these traps that lead to the buildup of hydrogen. Hydrogen is absorbed by thermal energy when steel is heated and is released when the absorbed energy reaches a critical threshold, which is the same as the activation energy of desorption. Consequently, the temperature at which hydrogen atoms are released is known as the desorption temperature. With quadrupole mass spectrometry, the amount of desorbed hydrogen is quantified. [11].

### *4.3 Hydrogen Permeation Test (HPT)*

The easiest method of measurement and the amount of diffusible hydrogen in steel are also determined by permeation testing. It is possible to determine and access steel's HE susceptibility if the quantity of diffusible hydrogen is known. This permeation test has been used in conjunction with other testing techniques to successfully test steel [30]. In essence, this permeation test uses a two-cell system, with an entering cell (also called a charge cell) and an oxidation cell (also called an exit cell) in each chamber. A steel membrane divides these two chambers [31]. The process of electrochemistry has been employed for hydrogen charging. After entering the cell to charge it, the hydrogen moves to the oxidation cell with the assistance of membrane [15].

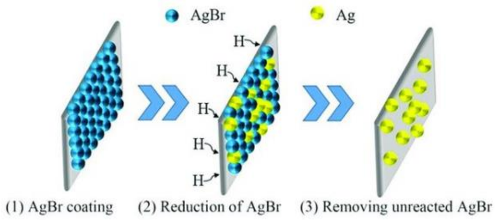


Figure 7. schematic diagram of HMT [29]

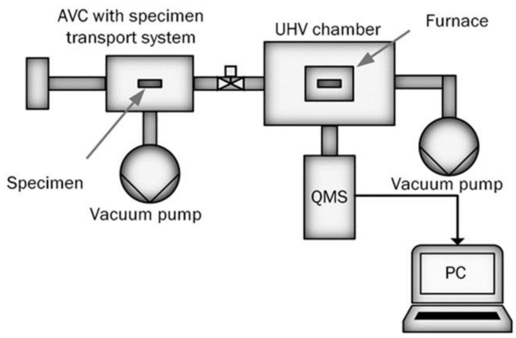


Figure 8. Schematic view of the TDS apparatus [11]

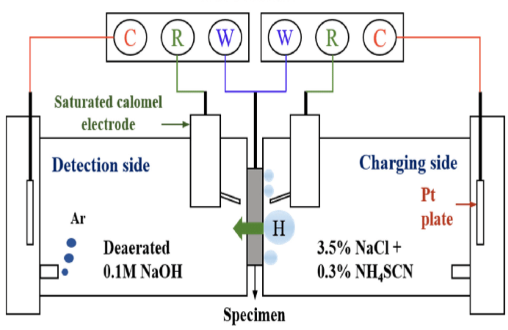


Figure 9 Schematic illustration of the electrochemical hydrogen permeation test [15]

### *4.4 Linearly Increasing Stress Test (LIST)*

This mechanical testing technique is used to find the HE in various material types. In this example, a sample was loaded and the applied stress was steadily increased until failure occurred. A load is applied by weight movement, and a motor regulates the load's rate of motion. Figure 10 shows the LIST method schematic. The specimen will fail whenever the threshold stress is reached in this load control HE measurement method, confirming the completion of the test. Using SEM, the fracture surfaces can be assessed after the LIST test [32]. Thus the impact of hydrogen on the material's interior microstructure can be determined. The most recommended, flexible, and user-friendly method for it is SEM. Additionally, SEM offers a three-dimensional image and shows fracture features like fisheyes, dimples, and micro voids [33 -34].

## 5. Preventive Measures of HE

The interactions between the hydrogen concentration and stress gradient cause hydrogen to diffuse toward and accumulate in the stress accumulation region. Fracture failure happens as the local hydrogen concentration approaches the critical value. Internal and external hydrogen are the two categories into which hydrogen sources are often divided. While hydrogen generated during service is external hydrogen caused by corrosion, hydrogen gas, and H2S gas acid environments, internal hydrogen is produced during material preparation procedures like melting, welding, pickling, and plating [35]. Based on the literatures researchers proposed and recommended so many preventive measures that restrict hydrogen diffusion in to the steel and any other metals.

In addition to proper material design, notches, abrupt and irregular variations, and residual stresses should be eliminated prior to processing [36]. Hydrogen, which is absorbed and could cause failure or damage, has been separated from the material by baking. Baking temperature varies depending on the substance being baked, as it is essentially a heat treatment technique. Using an acidic solution, the pickling process was used to remove some scale and oxide compounds from the material. Since this acid is what causes hydrogen to diffuse, mechanical methods like sandblasting, vapor blasting and grit blasting, will be used for reducing it [28].

Moreover, HE can be avoided by coating the base material with a protective layer and incorporating metal alloys into it. Mechanical plating, vacuum deposited coating, and organic coating are a few of the coating methods. Using effective inhibitors is also essential. When titanium is readily available in large amounts, its presence can lessen a hot stamped boron steel's HE susceptibility by producing titanium carbide within the material [21]. Certain authors claim that alloying aluminum can also aid in reducing the HE impact. Graphene and niobium coatings can also prevent material from HE. Steel is treated with cadmium to prevent hydrogen from leaking through. Diffusion of hydrogen becomes blocked when nickel is coated on steel. In order to prevent hydrogen from penetrating, a variety of coatings, including WC, TiC, TiN, TiO2, alumina, BN, and Cr2O3, have been employed [37].

Generally, there are two methods that can be used to prevent HE. First, surface treatments including coatings and modification treatments are applied. These methods are used to halt HE from the outside. The second tactic entails altering the material's microstructure by refining the alloy's microstructure and introducing or eliminating the appropriate alloy components [35].

### *5.1 Surface Coating*

Steels that are prone to hydrogen embrittlement, particularly lightweight, high-strength steels or low-cost alloy steels, should be able to be used in hydrogen-based economies thanks to hydrogen barrier coatings. Hydrogen barrier coatings are protective layers that have the ability to slow down, stop, or prevent hydrogen permeability [38]. They are made of materials with low intrinsic hydrogen diffusivity and solubility. When a coating is applied to a metal surface, hydrogen entrance into the alloy is inhibited, leading to high hydrogen resistance in the alloys [39]. When steels are treated to improve their resistance to air corrosion, a 1-3 μm thick oxide layer is formed on their metal surface. This process is known as surface blackening. Furthermore, alloys' susceptibility to HE can be decreased and hydrogen infusion effectively suppressed by surface coatings of Ni, Cd, Al, and Al–Ni complex coatings [35]. Moreover, as figure 10 illustrates, hard coatings like TiC, Al2O3, and Si3N4 are capable of significantly reducing hydrogen diffusion behavior [35]. Found that after coating the surface of stainless steel with a 1 μm-thick TiN film, the metal's hydrogen diffusion coefficient decreased by five orders of magnitude.

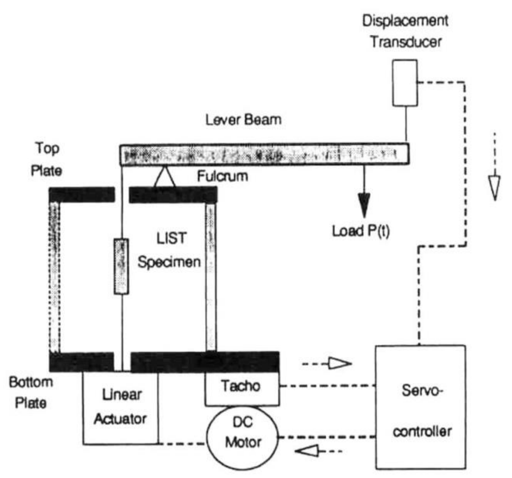


Figure 10 Schematic representation of the LIST apparatus [32]

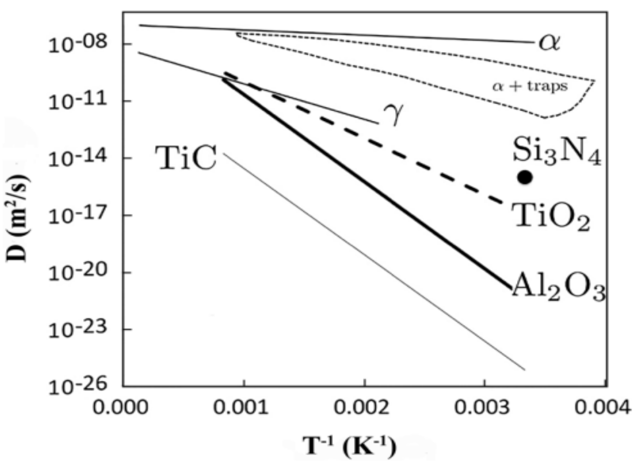


Figure 11 Temperature dependence of the hydrogen diffusion coefficient in different films [35]

The large difference in the rate of hydrogen diffusion between the austenite phase and the TiC and Al2O3 coatings suggests that these films may be a good barrier to enhance the HE resistance of austenite steels. When nickel is coated on steel, it prevents hydrogen from diffusing through. Many coatings have been used as a barrier to stop hydrogen permeability, such as WC, TiC, TiN, TiO2, alumina, BN, and Cr2O3. Coatings consisting of Pt, Cu, Cd, Ag, Al, and Au can help reduce the amount of hydrogen that migrates inside steel [33] [38]. Another way to prevent HE is to coat the base material with a protective layer and incorporate some metal alloys into it [40]. Mechanical plating, organic coating, and vacuum deposited coating are a few of the coating methods. Using strong inhibitors is also crucial. When titanium is widely accessible, its presence can lower the HE susceptibility of a hot stamped boron steel by forming titanium carbide inside the alloy [41]. According to some authors, alloying aluminum may also aid in reducing the HE effect. Coatings using niobium and graphene can also shield materials from HE [42].

### *5.2 Modifying Microstructure of Material*

Since the basic principles underlying the HE process are still poorly understood, developing microstructure design methods to reduce HE is difficult [43]. Nevertheless, there have been some recent advancements in this subject. Based on different literatures: Surface treatment, solute segregation and heterogeneity, grain boundary engineering, second-phase entrapment, and grain refining are some of these techniques [41, 44]. With rising Ni, Al, and Mo elemental concentrations and falling C, Si, P, and S elemental concentrations, HE will fall. For instance, it was found that the HE of the Mn–B steel rises with an increase in the C element level. Nevertheless, with C concentrations higher than 0.3%, the sensitivity to HE does not vary [17]. According to Xinfeng Li et al. [35], once the P element content was decreased, the threshold stress intensity factor of 4340 steels increased by a factor of five. P segregation may be hindered by a decrease in the concentration of Cr, Mn, Si, or an increase in the content of Mo and Ti. First-principles calculations [46] indicate that Al inhibits hydrogen diffusion more than Si in BCC iron. As a result, low HE sensitivity is found in bainitic steel with a high Al element content. The Fe–Mn–C steel's HE resistance is increased by Cu and Al components, which also boost the stacking fault energy and reduce the stress concentration at the grain boundaries. Furthermore, regular combinations of elements such as Mo, V, and Ti with C result in the formation of carbides, which improve the alloy's resistance to HE and act as permanent hydrogen traps [47].

Steels' HE is dependent on their microstructures. In particular, the highest HE susceptibility is found in the martensitic structure, which is followed in order by bainite, pearlite, and austenite [48]. HE susceptibility was lower in fastener steels having a pearlitic microstructure than in bainitic steel [35]. Although martensitic and pearlitic steels have the same strength level, pearlitic steel is known to have a greater HE resistance.

## 6. Result and discussion

The phenomenon of HE in steel and other materials is now well established. This study addresses materials that are prone to hydrogen penetration or diffusion, as well as the mechanisms and causes that lead to mechanical property degradation and hydrogen-related failures like HE. Preventive measures to get rid of or lessen hydrogen penetration in the material are talked about concurrently. These preventative measures can lower the likelihood of HE by obstructing the diffusion of hydrogen. The table below summarizes the relevant prior related studies in summary form. Following investigations into measurement strategies to determine the hydrogen content of steel, a variety of techniques have been employed, including the HMT, TDS, HPT, LIST, and GC. With the distinct benefits of each technique, researchers can analyze diffusion behavior through HPT, exact quantification with TDS, surface mapping with HMT, and many other facets of hydrogen activity in steel. Parallel research on preventive measures against HE revealed a multidisciplinary strategy that includes diffusion barrier coatings, modification of microstructure, new materials development with improved hydrogen-trapping capabilities, coating selection and design, and mechanical design optimization. By decreasing hydrogen absorption into the material, increasing hydrogen trapping capacity, improving material characteristics, or altering mechanical design features to lessen stress concentrations and minimize embrittlement, these preventive approaches seek to reduce HE. Researchers can create complete methods for effectively understanding, mitigating, and preventing hydrogen embrittlement in steel structures and components by combining insights from measuring techniques with preventative measures. By working together, it can be possible to improve testing methods and preventive measures, which leads to a better knowledge of hydrogen embrittlement mechanisms and useful solutions to protect steel materials from its harmful consequen

Table 1 studies related with Mechanisms Causing HE

| Ref. # | Author | Types of Mechanisms Causing HE | Results and conclusions |
|---|---|---|---|
| [19] | Djukic, M. et al. | HEDE | Results indicate a simultaneous action of the hydrogen-enhanced decohesion (HEDE) and hydrogen-enhanced localized plasticity (HELP) mechanisms of HE, depending on the local concentration of hydrogen in investigated steel. |
| [21] | Kappes, M.et al. | | The cohesive strength of lattice planes or interface boundaries is decreased in the presence of hydrogen. |
| [15] | Zheng,W. et al | | The atomic bonds at the crack's tip weaken due to the accumulation of hydrogen at the crack tip. |
| [17] | Koyama, M. et al. | HIE | Hydrides first appeared in the stress field of the fracture, and instead of growing from individual hydrides, they generated new hydrides in the stress fields of the other hydrides to reach vast sizes. |
| [18] | Pérez,F. et al. | HELP | • Investigated the HELP mechanism in high-strength steels.<br>• Found that hydrogen-induced softening and localized plasticity contribute to embrittlement, especially at stress concentrations. |
| [22] | Martin, M. et al. | | • Developed a multiscale model to elucidate the HELP mechanism.<br>• Identified hydrogen trapping and dislocation interactions as key factors contributing to embrittlement. |
| [21] | Kappes,M .et al. | AIDE | • Studied AIDE mechanism in high-strength alloys using atomistic simulations.<br>• Demonstrated that hydrogen-induced dislocation emission significantly reduces the material's ductility. |
| [5] | Pradhan,A .et al. | HAM | • Used molecular dynamics simulations to investigate the role of hydrogen in micro-fracture initiation.<br>• Found that hydrogen accumulates at grain boundaries, facilitating micro-fracture. |

Table 2. studies related with Measurement of Hydrogen Concentration in Steel

| Ref. # | Author | Types of Measurement | Results and conclusions |
|---|---|---|---|
| [27] | Ronevich, J. et al. | HMT | Developed HMT for mapping hydrogen concentration on steel surfaces. |
| [14] | Silva, S. et al. | TDS | Utilized TDS to quantify hydrogen concentration in steel samples. |
| [30] | Figueroa, D. et al. | HPT | Conducted HPT to study hydrogen diffusion behavior in steel. |
| [34] | GAMBOA, E. et al. | LIST | Employed LIST to evaluate the susceptibility of steel to hydrogen embrittlement. |

Table 3. Studies related with Preventive Measures of HE

| Ref. # | Author | Preventive Measures | Results and conclusions |
|---|---|---|---|
| [40] | Fan, Y. et al. | Coating selection and design | • Investigated the effectiveness of various coatings in preventing hydrogen embrittlement.<br>• Found that certain coatings reduce hydrogen diffusion into the material, mitigating embrittlement. |
| [36] | Ćwiek,J. et al. | Mechanical design optimization | • Investigated the role of mechanical design features, such as notch geometry and stress concentration reduction, in mitigating HE.<br>• Recommended design modifications to reduce embrittlement. |
| [35] | Li, X. et al. | Modifying Microstructure of Material | altering the material's microstructure by refining the alloy's microstructure and introducing or eliminating the appropriate alloy components |

## 6. Conclusion

This work addresses the causes, mechanisms, measurement techniques, and hydrogen-related failures, such as HE, in steel material which is susceptible to hydrogen penetration or diffusion. Preventive measures intended to eliminate or minimize hydrogen penetration in steel are discussed about at the same time. By preventing hydrogen diffusion, these preventative measures may reduce the probability of hydrogen catastrophes. The conclusions drawn from the review of academic literature that gives a general overview of hydrogen embrittlement in steel are as follows.

- When the diffusible hydrogen content above the critical hydrogen concentration, HE occurs in the material, and the degree of HE depends on the hydrogen concentration.
- Steel loses its ductility and toughness as its carbon content rises or its strength levels exceed 1000 MPa, making it more susceptible to fracture even in situations with comparatively little stress.
- The main causes that raise the possibility of hydrogen embrittlement in steel are environmental factors, material susceptibility, and load (stress) conditions.
- There is currently no standard HE mechanism for all materials; all of the current HE mechanisms are only relevant to certain materials in particular applications.
- The most widely used experimental methods for measuring concentrations and analyzing hydrogen trapping in steel are now TDS and GC with TCD.
- There are two ways to prevent HE from occurring. First, surface treatments including coatings and modification treatments are applied. These methods are used to prevent HE from the outside. The second method involves modifying the material's microstructure by optimizing the alloy's microstructure and introducing or eliminating the appropriate alloy elements.
- Steel's HE will drop if the amounts of the elements C, Si, P, and S are decreased or the amounts of Ni, Al, and Mo are increased. Additionally, elements like Mo, V, and Ti typically combine with C to form carbides, which strengthen the alloy's resistance to HE by functioning as long-term hydrogen traps.

## Declaration

There are no possible conflicts of interest that the authors have disclosed about the research, writing, or publication of this article. Additionally, the authors declared that no specific authorization or ethical committee approval was needed for this piece, which was written entirely on its own and in compliance with international publication and research ethics.

## Author Contributions

Biniyam Ayele Abebe: Original draft writing, conceptualization, methodology, and data collection.
Ekrem Altuncu: Teaching and supervision, structure – assessment & editing.

## Nomenclature

AIDE : Adsorption Induced Dislocation Emission
AHSS : Advanced High Strength Steels
APT : Atom probe tomography
CPFEM : Crystal plasticity finite element method
DIC : Digital image correlation
EAC : Environmentally Assisted Cracking
GC : Gas Chromatography
HAM : Hydrogen Assisted Micro-Fracture Mode
HE : Hydrogen Embrittlement Potential
HEDE : Hydrogen-Enhanced Decohesion Mechanism

HELP : Hydrogen-Enhanced Local Plasticity Model
HIE : Hydride-Induced Embrittlement
LIST : Linearly Increasing Stress Test
HPT : Hydrogen Permeation Test
TCD : Thermal Conductivity Detectors
TDS : Thermal Desorption Spectroscopy
HMT : Hydrogen Microprint Technique
MD : Molecular dynamics
NMI : Non-Metallic Inclusions
SEM : Scanning Electron Microscopy
SKPFM : Scanning Kelvin probe force microscopy
SIMS : Secondary ion mass spectroscopy
FCC : Face-Centered Cubic
BCC : Body-Centered Cubic
HCP : Hexagonal Close-Packed

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