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Table of Content

1. Introduction.....	4
2. Origins of Hydrogen	5
2.1 Natural and Combined Forms	5
2.2 Production of Hydrogen	5
3. Structural Changes Due to Hydrogen Absorption in Metals	6
3.1 Hydrogen in the Liquid State.....	6
3.2 Hydrogen in the Solid State	6
4. Metallographic Examination	7
4.1 Optical Microscopy	7
4.2 Electron Microscopy	7
5. Effects of Hydrogen on Ferrous Metals	8
5.1 Mechanical Properties	8
5.2 Microstructural Impacts.....	9
6. Consequential Effects on Metal Processing and Welding	10
6.1 Processing Challenges	10
6.2 Welding Defects	10
7. Literature Survey and Analysis	10
7.1 Mechanisms of Hydrogen Embrittlement.....	10
7.2 Characterization Techniques.....	11

8. Recommendations and Future Work.....	12
8.1 Material Selection.....	12
8.2 Preventive Coatings.....	12
8.3 Advanced Characterization	12
8.4 Welding Practices.....	12
8.5 Research Areas.....	12
Conclusion	12

1.Introduction

As a clean energy carrier and efficient reducing agent, hydrogen has become a key facilitator in the global effort to achieve net-zero energy goals. Its significance extends to several fields, including as industrial operations like the extraction of metals from ores and the generation and storage of energy. Because hydrogen makes cleaner and more sustainable approaches possible, it has the potential to completely transform conventional carbon-intensive industries.

Hydrogen can be used as both a fuel and a reducing agent in metal processing, especially in procedures like iron extraction. But there are a lot of difficulties because of the special characteristics of hydrogen, such as its small atomic size, high diffusivity, and high reactivity. Materials easily react with hydrogen, changing their microstructure and thus jeopardizing their mechanical qualities. Because hydrogen absorption in metals can result in embrittlement, porosity, and cracking, these interactions are especially problematic. Hydrogen causes structural alterations in metals in both their liquid and solid forms, which have a significant impact on fabrication and processing methods, particularly welding. Significant obstacles stand in the way of attaining the intended material performance and structural reliability due to hydrogen-induced flaws, such as gas porosity during casting and hydrogen cracking in welded joints.

This research explores the origins of hydrogen, its absorption methods in metals, and the ensuing structural alterations in order to solve these issues. It also looks at metallographic methods, such optical and electron microscopy, to show how hydrogen affects metals visually. Along with the wider ramifications for industrial operations, the impacts on ferrous metals—specifically, their mechanical properties—are thoroughly examined. The article ends with suggestions for reducing hydrogen-related problems, highlighting the significance of continued study and creative fixes in developing environmentally friendly metal processing methods.

2. Origins of Hydrogen

2.1 Natural and Combined Forms

The most prevalent element in the universe, hydrogen, is essential to both industrial and natural processes. There are two main varieties of it:

- **Natural State:** The Earth's atmosphere naturally contains trace amounts of molecular hydrogen (H_2). Because of its low molecular weight, which enables it to evade Earth's gravitational pull, atmospheric hydrogen is uncommon while being abundant throughout the cosmos.
- **Combined Forms:**
 - **Water (H_2O):** Water (H_2O): The most important and accessible source of hydrogen, water is the main raw material used in the electrolysis process to produce hydrogen.
 - **Hydrocarbons:** Methane (CH_4) and other organic molecules found in natural gas serve as feedstocks for reforming procedures that produce hydrogen. These resources provide a link between greener hydrogen technologies and conventional fossil fuels.

2.2 Production of Hydrogen

There are various ways to create hydrogen, which are grouped according to their feedstock and environmental impact:

- **Electrolysis:**

Electrolysis is a clean and sustainable way to produce hydrogen by splitting water into hydrogen and oxygen using electricity, ideally from renewable sources. Achieving net-zero energy targets requires using this "green hydrogen" generation method.
- **Thermochemical Processes:**

Methane and steam react to produce hydrogen and carbon monoxide, which are then transformed into carbon dioxide in the commonly used process known as steam methane reforming (SMR). Coal gasification is a carbon-intensive process that produces hydrogen by breaking down coal through high-temperature reactions.
- **Biological Processes:**

Under particular circumstances, several microorganisms, including bacteria and algae, create hydrogen. This new technique uses natural biological processes to produce hydrogen in an eco-friendly manner.

3. Structural Changes Due to Hydrogen Absorption in Metals

3.1 Hydrogen in the Liquid State

High temperatures cause hydrogen atoms to be very mobile, which speeds up hydrogen absorption in liquid metals. At the metal's liquid-solid boundary, hydrogen usually creates gas bubbles when added to liquid metal. As the bubbles form, the porosity may rise throughout the solidification process. These bubbles of hydrogen gas cause holes that weaken the material's overall strength and structural integrity by upsetting the metal's microstructure. Hydrogen also segregates at the grain boundaries when the metal cools and solidifies, creating flaws at these crucial sites and intensifying weakening effects. A catastrophic failure under stress may result from this mechanism, which also reduces mechanical qualities, especially ductility.

3.2 Hydrogen in the Solid State

Propagation is how hydrogen atoms enter the metal lattice and interact with microstructural elements in solid metals to absorb hydrogen. A number of variables, including temperature, material composition, and the existence of microstructural flaws, affect the pace and magnitude of hydrogen diffusion.

- **Absorption and Diffusion:**

The characteristics of the metal can be drastically changed by the absorption and diffusion of hydrogen atoms, which move through the crystal lattice once within the metal and frequently gather at particular locations. Hydrogen atoms can travel and concentrate more easily when dislocations, grain boundaries, and other flaws are present. Particularly at high hydrogen concentrations, the ensuing diffusion process may be a factor in material property changes.

- **Hydrogen Traps:**

There are two types of hydrogen traps, which are microstructural sites where hydrogen atoms can be trapped:

- **Reversible Traps:** Interstitial sites and vacancies are examples of reversible traps, which allow hydrogen atoms to be momentarily held before being released. Although these traps are less likely to permanently harm the metal, they can nevertheless have an impact on its mechanical characteristics and diffusion behavior.
- **Irreversible Traps:** Because they involve carbides, oxides, and precipitates, these traps are more troublesome. In addition to capturing hydrogen atoms, these sites have a substantial impact on the microstructure of the metal, resulting in long-term embrittlement, a reduction in ductility, and an increased vulnerability to cracking.

4. Metallographic Examination

4.1 Optical Microscopy

One of the main methods for analyzing metal microstructure and identifying the consequences of hydrogen absorption is optical microscopy. Because hydrogen interacts directly with the structure of the metal, surface and subsurface porosity can be seen in the case of hydrogen-induced damage using optical microscopy. Under magnification, hydrogen absorption frequently results in the formation of gas bubbles or voids. The total strength of the material is reduced as a result of these voids, which usually appear at grain boundaries or other microstructural characteristics. Furthermore, microcracks, a sign of embrittlement, could be seen. The appearance of these fissures, which frequently take the form of dark lines, is another indication that the material has been weakened by hydrogen absorption.

4.2 Electron Microscopy

At a finer scale, electron microscopy techniques offer deeper insights into the effects of hydrogen on the material and offer higher resolution than optical microscopy, which is useful for larger-scale investigations. The following electron microscopy methods are especially helpful for researching damage caused by hydrogen:

- **Scanning Electron Microscopy (SEM):**

SEM is used to examine material fracture surfaces and offers important insights into the kinds of fractures brought on by hydrogen embrittlement. Fractures caused by hydrogen are frequently intergranular and brittle, which means they happen at grain boundaries. SEM makes it possible to examine these fractures in detail and provides visible proof of the impact of hydrogen on the fracture toughness of the material. The absence of plastic deformation is a common characteristic of these fractures, which supports the hydrogen embrittling action.

- **Transmission Electron Microscopy (TEM):**

Defects at the nanoscale caused by hydrogen absorption can be seen thanks to TEM. For instance, TEM can be used to identify hydrogen-induced voids, which are created at the atomic level. These gaps aid in the metal's embrittlement and are important markers of hydrogen-induced material deterioration. Researchers can better understand how hydrogen atoms disperse and collect at particular locations by using TEM to gain insights into the interplay between hydrogen and the material's microstructure.

- **Atom Probe Tomography (APT):**

APT is an effective method for mapping the atomic-level distribution of hydrogen atoms. Investigating how hydrogen builds up in certain microstructural areas, such as grain boundaries, dislocations, and other trapping sites, is made easier with the use of this approach. By providing a three-dimensional representation of the hydrogen distribution, APT helps to clarify how hydrogen contributes to the material's deterioration.

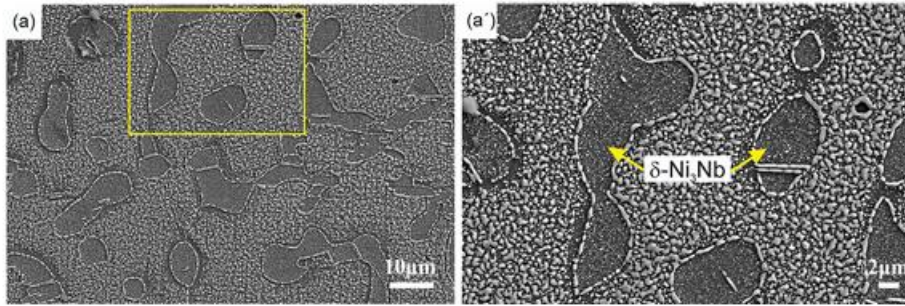


Fig1 : SE images showing hydrogen decoration with charged specimens could be used to emphasize hydrogen effects during metallographic studies.

The picture highlights how SEM may show the presence of particular phases like δ -Ni₃Nb as well as the complex microstructural characteristics of materials. Understanding the material's mechanical characteristics and how variables like hydrogen absorption impact them requires knowledge of this information.

5. Effects of Hydrogen on Ferrous Metals

5.1 Mechanical Properties

The mechanical characteristics of ferrous metals are significantly impacted by hydrogen absorption, especially in terms of brittleness and ductility reduction. There are numerous important techniques to observe the effects of hydrogen-induced damage:

- **Reduced Ductility:**
Softness, or a material's capacity to withstand plastic deformation without breaking, is significantly decreased by hydrogen embrittlement. The metal's ability to deform under stress may be hampered by hydrogen atoms interfering with dislocation movement within the material. One of the main causes of the brittleness and cracking susceptibility of metals exposed to hydrogen is this loss of ductility.
- **Increased Brittle Fracture:**
Under applied stress, the presence of hydrogen in ferrous metals speeds up the propagation of cracks. In hydrogen-embrittled materials, cracks usually spread at grain boundaries or other weak spots, which accelerates the material's failure compared to when hydrogen is absent. Usually brittle, these fractures show little to no plastic deformation before failing. The material is far more prone to abrupt, catastrophic failure because of its brittle fracture tendency, especially in high-stress situations.
- **Hydrogen-Induced Delayed Fracture (HIDF):**
Hydrogen-induced delayed fracture is one of the most pernicious consequences of hydrogen (HIDF). This phenomena describes how materials

that have absorbed hydrogen break down over time. In contrast to abrupt failure, HIDF happens after the material has been subjected to stress and hydrogen for a while.

5.2 Microstructural Impacts

- **Strain-Induced Vacancies:** Hydrogen weakens the material by promoting the creation of vacancies in the crystal lattice.
- **Disruption of Grain Boundaries:** Hydrogen builds up at grain borders, weakening them and encouraging the start of cracks.
- **Void Coalescence:** The presence of hydrogen in a material can cause voids to grow, which eventually combine to weaken the structure even more.
- **Changes in Phase Distribution:** Exposure to hydrogen can change phase distributions, especially in high-strength steels, which can impact the strength and durability of the material.

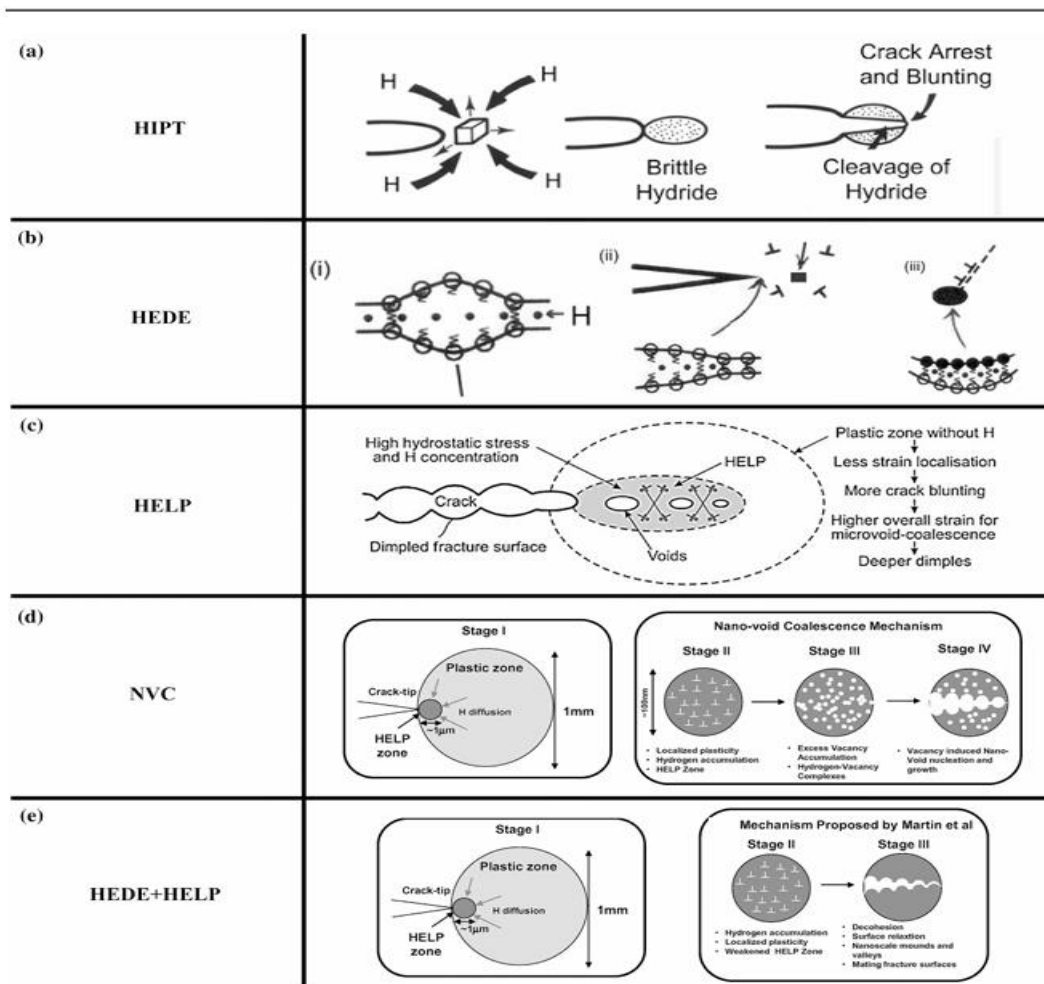


Fig 2 : Schematic diagrams of HE mechanisms (HELP, HEDE, etc.) clearly relate to the microstructural impacts and mechanical effects of hydrogen embrittlement discussed in this section.

Five hydrogen embrittlement (HE) methods are contrasted in the image: (a) HIPT, (b) HEDE, (c) HELP, (d) NVC, and (e) HEDE+HELP. Brittle hydrides that cause crack

initiation and propagation are seen in HIPT. HEDE emphasizes how hydrogen diffusion promotes cracks and lowers fracture toughness. Crack blunting and hydrogen-induced localized plasticity are demonstrated by HELP. NVC illustrates how fracture propagation is caused by nano-void development and coalescence. Combining HEDE and HELP, HEDE+HELP illustrates complicated material behavior under the impact of hydrogen and stress.

6. Consequential Effects on Metal Processing and Welding

6.1 Processing Challenges

Hydrogen creates a number of important processing issues that might deteriorate material qualities during the metal extraction and casting processes. Gas porosity, in which hydrogen bubbles during solidification, is one of the main problems. The material becomes porous as a result of these trapped gas bubbles, weakening the finished product. Furthermore, there is hydrogen segregation, which results in weak places in the metal as hydrogen builds up at certain locations, especially at grain boundaries. This localized buildup might result in decreased overall mechanical performance and worsen material failure under stress.

6.2 Welding Defects

Hydrogen-induced cracking (HIC) is a serious issue in welding processes, especially in the weld's heat-affected zone (HAZ). When hydrogen permeates the material during welding, it can combine with residual stresses—which are increased in the HAZ because of the fast cycles of heating and cooling—to create cracking. When these residual strains are paired with the high hydrogen level, the weld may fail catastrophically. Remedial techniques like preheating are used to lessen the migration of hydrogen into the metal in order to reduce these dangers. Post-weld heat treatment (PWHT) is also frequently used to release trapped hydrogen, which lowers the risk of HIC and improves the welded joint's overall integrity.

7. Literature Survey and Analysis

7.1 Mechanisms of Hydrogen Embrittlement

Numerous mechanisms involved in the complex phenomena of hydrogen embrittlement (HE) have been thoroughly examined in the literature. Hydrogen-Enhanced Decohesion (HEDE) and Hydrogen-Enhanced Localized Plasticity (HELP) are the two main mechanisms.

- **Hydrogen-Enhanced Decohesion (HEDE)** is used to describe how the presence of hydrogen weakens atomic bonding at interfaces, such as grain boundaries or the contact between phases. Diffusing into these areas, hydrogen atoms weaken the material's cohesiveness, increasing its vulnerability to stress-induced cracking and fracture.
- **Hydrogen-Enhanced Localized Plasticity (HELP)** focuses on how hydrogen contributes to localized increases in the plastic deformation of materials.

Hydrogen facilitates dislocation migration by lowering the flow stress of metals. The material may become more prone to fracture under stress as a result of localized strain concentrations brought on by this increased flexibility.

7.2 Characterization Techniques

Many sophisticated characterisation methods have been developed to comprehend the interaction of hydrogen with metals. One method for measuring the amount of hydrogen released from metals when heated is thermal desorption spectroscopy (TDS). TDS offers useful information about hydrogen concentrations and the kinds of traps in the material by examining the desorption peaks. Another effective technique for mapping the distribution of hydrogen in a material at high spatial resolution is secondary ion mass spectroscopy, or SIMS. By using this method, scientists can see how hydrogen builds up at particular spots, including dislocations and grain boundaries, giving them a better understanding of how hydrogen behaves in metals. In order to comprehend the mechanics of hydrogen embrittlement and create more robust materials, these sophisticated characterisation techniques are crucial. They also help develop solutions to reduce hydrogen-related failures in metal processing.

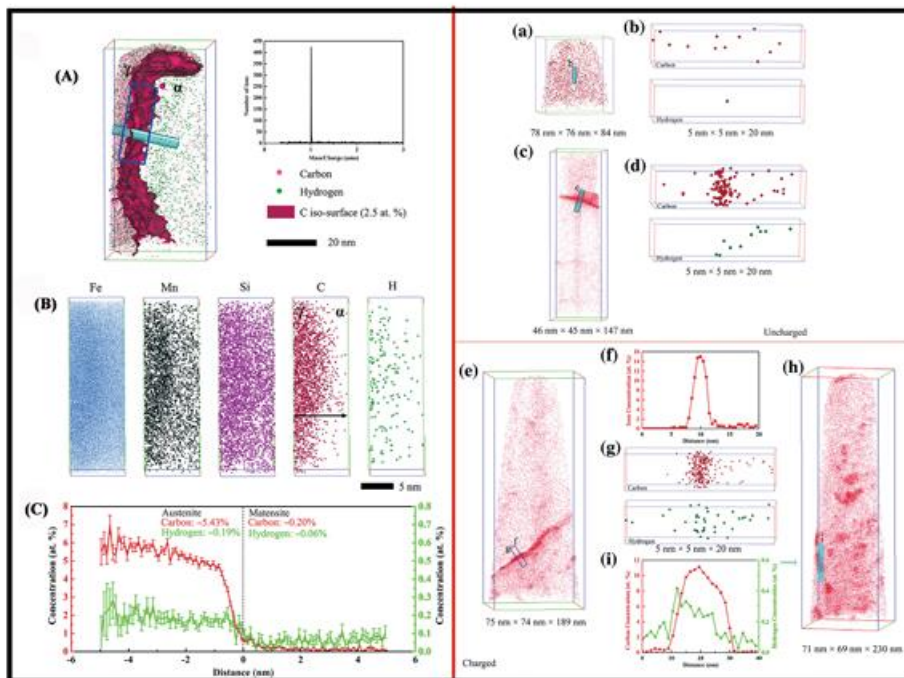


Fig 3 : The picture shows both 2D and 3D assessments of the distribution of hydrogen and carbon in steel. Whereas hydrogen is uniformly distributed, carbon clusters at austenite-martensite contacts. Higher hydrogen concentrations are found in areas with lower carbon content, according to concentration profiles, which exhibit an inverse relationship.

8. Recommendations and Future Work

8.1 Material Selection

It is crucial to concentrate on creating alloys that are less prone to hydrogen absorption in order to lessen the impacts of hydrogen embrittlement. The risk of embrittlement can be considerably decreased by materials that have a lower propensity to absorb hydrogen or that create stronger connections with hydrogen. New alloying elements and compositions should be investigated by researchers, especially those that improve the metal's resistance to damage from hydrogen while preserving its mechanical qualities.

8.2 Preventive Coatings

Effective coatings can be applied to metals to act as a barrier against hydrogen intrusion, lowering the likelihood of embrittlement and inhibiting its absorption. It is possible to create coatings that prevent hydrogen diffusion, like ceramic or metallic films. Future research should concentrate on creating coatings that are strong, affordable, and able to tolerate mechanical loads and high temperatures, particularly in demanding industrial applications.

8.3 Advanced Characterization

Advanced characterisation methods like Transmission Electron Microscopy (TEM) and Atom Probe Tomography (APT) should be used further to obtain a deeper understanding of the distribution of hydrogen in metals. These methods can assist visualize the interactions between hydrogen and microstructural features like as precipitates, dislocations, and grain boundaries at the atomic level. This will help in the development of mitigation methods and provide insightful information on problems caused by hydrogen.

8.4 Welding Practices

Metal fabrication relies heavily on welding techniques, which are particularly vulnerable to hydrogen-induced cracking (HIC). Optimized preheating and post-weld heat treatment (PWHT) procedures ought to be used in order to reduce this danger. While PWHT makes it easier for stored hydrogen to be released, preheating helps minimize thermal stresses by lowering the temperature gradient. The goal of ongoing research should be to improve these procedures for different welding situations and materials.

8.5 Research Areas

Exciting prospects for managing the effects of hydrogen on metals are presented by the developing field of additive manufacturing. It could be possible to build components that are more resistant to hydrogen embrittlement by controlling the microstructure and material properties layer by layer. For companies that are increasingly using additive manufacturing for complicated components exposed to hydrogen, more research in this field may yield creative solutions.

8. Conclusion

The processing and structural integrity of metals is significantly hampered by hydrogen embrittlement, particularly in sectors that are switching to hydrogen as a primary energy source. Metals' mechanical characteristics are changed when hydrogen is absorbed by them, increasing the likelihood of failure, especially in high-strength materials. The mechanics underlying hydrogen embrittlement, its consequences for ferrous metals, and its influence on different metal processing methods, such as welding, have all been highlighted in this research. Industries can better control the dangers related to hydrogen by developing efficient mitigation techniques, such as the creation of alloys, improved welding techniques, and sophisticated coatings. Furthermore, to guarantee that hydrogen can be used safely and effectively in a hydrogen-based economy without sacrificing material reliability, more research into cutting-edge characterization methods and material science advancements will be essential.

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