



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Student Name: Abhishek Hasmukhbhai Vagadiya

ID number: 2410890

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Abstract

Shifting to a net-zero energy policy means moving away from carbon-based fuels and reducing agents. Hydrogen is a promising alternative. We can produce hydrogen through electrolysis, using renewable energy, and use it in various industrial processes like extracting iron. However, storing and transporting hydrogen is challenging due to its small size, reactivity, and potential effects on materials.

This paper looks at where hydrogen comes from, both in its natural state and when combined with other substances. It also explores how hydrogen affects metals during extraction, casting, and fabrication. The paper provides a clear analysis of how metals change structure when they absorb hydrogen in both liquid and solid forms. It includes studies using optical and electron microscopy to examine these changes.

Additionally, the paper evaluates how hydrogen absorption impacts the mechanical properties of ferrous metals, pointing out issues like embrittlement and degradation. It also considers how hydrogen affects metal processing, especially during welding, which can create challenges for fabrication and structural integrity. This study emphasizes the need for better hydrogen management strategies in metallurgical applications to ensure reliability and performance in a hydrogen-driven economy.

Introduction

Transitioning to a net-zero energy policy is essential for tackling climate change and necessitates a departure from carbon-based fuels. Hydrogen emerges as a clean fuel and a highly effective reducing agent in industrial processes, such as the reduction of iron ore.

However, the utilization of hydrogen also presents challenges, particularly regarding its interactions with metals. This report explores the sources of hydrogen, its effects on metal structures—particularly the phenomenon of hydrogen embrittlement—and its implications for manufacturing processes like welding, where it can lead to defects such as porosity and cracking.

Backed by metallographic evidence, the report emphasizes the mechanical challenges that stem from hydrogen absorption, which can compromise ductility and overall performance in ferrous metals. To address these issues, the report concludes with recommendations for managing hydrogen exposure, optimizing material selection, and enhancing welding techniques to safely integrate hydrogen into industrial applications.

1. Origins of Hydrogen

Hydrogen is a fundamental element that exists in nature in two primary forms: as a free element and as part of various compounds. In its elemental state, hydrogen accounts for a small fraction of the Earth's atmosphere. However, it is predominantly found in combined forms, including water (H₂O) and various hydrocarbons, which are organic compounds consisting of hydrogen and carbon. These combined forms serve as the principal sources of hydrogen production.

One of the most sustainable and environmentally friendly methods for generating hydrogen involves the process of electrolysis. This technique utilizes renewable energy sources, such as solar, wind, or hydroelectric power, to separate water into its constituent elements: hydrogen and oxygen. In this process, an electrical current is passed through water, causing it to disassociate into hydrogen gas and oxygen gas. The hydrogen produced through electrolysis is referred to as green hydrogen because it is generated without emitting any greenhouse gases.

This approach to hydrogen production is significantly more beneficial for the environment compared to traditional methods, such as steam methane reforming (SMR). SMR is a widely used technique that involves reacting natural gas with steam to produce hydrogen, but it also generates carbon dioxide as a byproduct, contributing to greenhouse gas emissions and climate change. In contrast, electrolysis powered by renewable energy sources provides a cleaner alternative, aligning with global sustainability goals and reducing reliance on fossil fuels.

The origins of hydrogen can be categorized into the following:

- **Natural Hydrogen:** Natural hydrogen is found in volcanic gases and in small amounts in natural gas. Although it is not abundant, people are becoming more interested in exploring natural hydrogen because it could be a clean energy source.
- **Industrial Production:** Most hydrogen is made through methods like steam methane reforming, partial oxidation of hydrocarbons, and coal gasification. These methods work well but produce a lot of carbon dioxide. To meet net-zero emissions goals, we need to use carbon capture technologies with these methods.
- **Renewable Sources:** We can produce hydrogen sustainably through electrolysis powered by renewable energy sources like wind, solar, and hydroelectric power. This method creates "green hydrogen," which is important for reducing carbon emissions in different industries.

Recent advancements in hydrogen production have introduced emerging technologies such as:

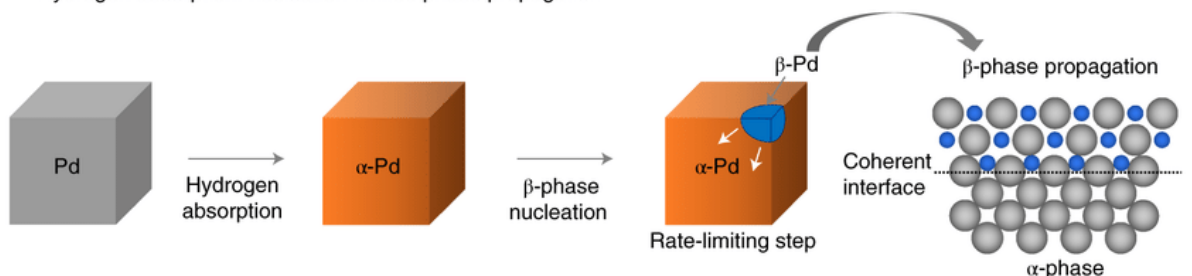
- **Photocatalysis:** This method uses sunlight to split water into hydrogen and oxygen. It can be scaled up and may reduce costs.
- **Biological Production:** This approach uses microbes to generate hydrogen from organic matter, providing a sustainable and low-energy way to produce it.
- **Plasma-assisted Processes:** This technique uses plasma energy to break down hydrocarbons into hydrogen and carbon black. It creates possibilities for businesses to work together in new ways.

2. Structural Changes Due to Hydrogen Absorption

Hydrogen absorption into metals induces notable structural changes, depending on the state of the metal:

- **Liquid State:** Hydrogen has a unique behavior when it dissolves in molten metals, where it plays a critical role in influencing the material's physical properties. When hydrogen is present in a molten metal, it alters the viscosity, making it flow more easily, and affects its fluidity, which is the ability of the metal to fill molds and conform to shapes during casting. Additionally, hydrogen impacts the solidification process; as the molten metal cools and transitions to a solid state, the dissolved hydrogen can precipitate out in the form of bubbles. These bubbles create voids within the solidified metal, resulting in porosity. Porosity not only undermines the integrity of cast components but also negatively affects their mechanical properties, such as strength, ductility, and fatigue resistance, ultimately compromising the performance of the finished product.
- **Solid State:** In solid metals, hydrogen behaves differently than in the liquid state. It diffuses through the crystalline structure of the metal in an interstitial manner, meaning it occupies spaces between the larger metal atoms. This diffusion causes hydrogen to accumulate at microstructural defects, including grain boundaries and dislocations. These areas are points of weakness within the metal's structure. The presence of hydrogen at these sites can lead to a range of phenomena, such as embrittlement, which makes the metal more susceptible to cracking and failure under stress. Furthermore, this accumulation can hinder the metal's ability to deform plastically, significantly impacting its overall mechanical properties and durability under mechanical loads.

a Hydrogen absorption: nucleation-limited phase propagation



b Hydrogen desorption: surface-limited recombination

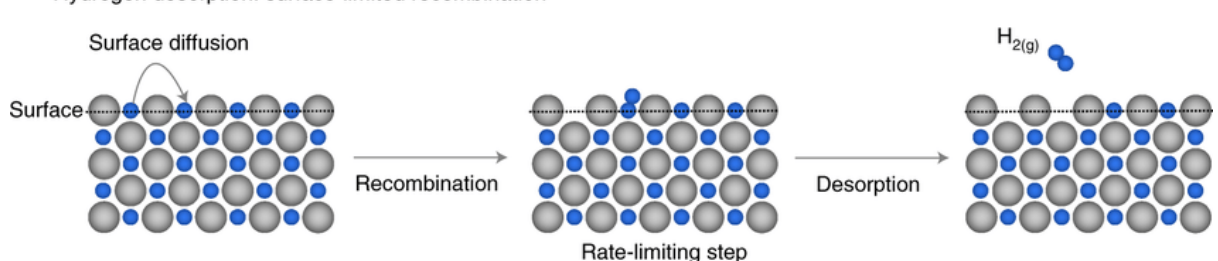


Figure 2 Hydrogen absorption solid state

- **Hydrogen Embrittlement (HE):** A reduction in ductility and toughness, making metals susceptible to cracking under tensile stress.

- Hydride Formation: In metals like titanium and zirconium, hydrogen reacts to form brittle hydrides, altering the microstructure and mechanical behavior.
- Decohesion: Accumulated hydrogen reduces the cohesive strength between atoms, promoting crack initiation and propagation.

Further exploration into structural impacts reveals:

- Micro void Coalescence: Hydrogen facilitates the formation and growth of micro voids at inclusions and second-phase particles within a material. This nucleation process weakens the structural integrity and accelerates fracture, increasing the likelihood of failure.
- Grain Boundary Weakening: The accumulation of hydrogen at grain boundaries can result in intergranular cracking, where cracks initiate along the interfaces of individual grains. This significantly compromises the mechanical integrity of the material, making it more susceptible to stress.
- Phase Transformations: In specific alloys, the absorption of hydrogen can induce phase transformations that alter the material's properties. These changes may impact hardness and strength, thus influencing the performance of the alloy in hydrogen-rich environments.

3. Metallographic Examination

Metallographic studies provide essential insights into the changes that metals experience when exposed to hydrogen. These evaluations utilize both optical and electron microscopy techniques:

- Optical Microscopy: This technique is crucial for examining macrostructural characteristics in materials, particularly those affected by hydrogen. It effectively reveals significant porosity resulting from the formation of hydrogen gas bubbles during the solidification process of metals. Furthermore, optical microscopy aids in identifying surface defects and inclusions that can serve as potential hydrogen traps. Understanding these features is essential for assessing how hydrogen interacts with a material's surface, which can influence its overall performance and longevity.

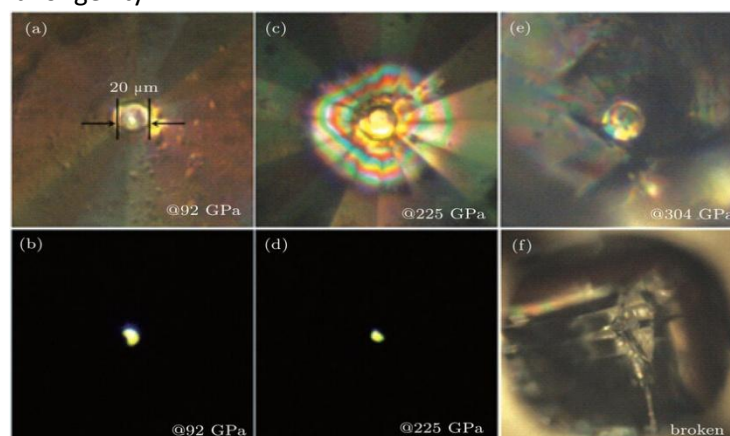


Figure 3.1 Optical microscopy of Hydrogen

- Electron Microscopy: This advanced method provides high-resolution imaging, allowing for the exploration of microstructural changes within materials. It is particularly valuable for analysing the effects of hydrogen on metallic structures. Key techniques include:

- Transmission Electron Microscopy (TEM): TEM enables researchers to visualize the internal structure of materials at the atomic level. It effectively identifies the presence and distribution of hydride phases within the metal matrix, which is important for understanding how hydrogen affects the material's mechanical properties and stability.

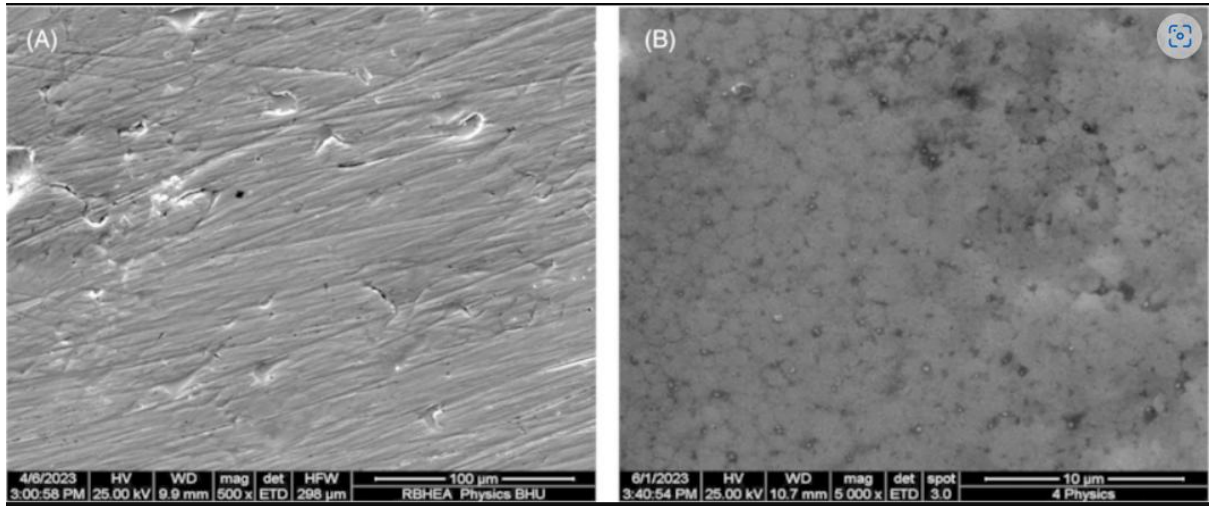


Figure 3.2 Electron Microscopy of Hydrogen
(A) before hydrogen absorption (B) after 10-cycle absorption

- Scanning Electron Microscopy (SEM): SEM is employed to conduct detailed investigations of fracture surfaces. By analysing these surfaces, it reveals complex patterns of crack propagation resulting from hydrogen assistance, demonstrating how hydrogen can facilitate the growth and expansion of cracks in the material.
- Energy-Dispersive X-ray Spectroscopy (EDS): Often used in conjunction with electron microscopy techniques, EDS is an analytical tool that detects and quantifies the elemental composition of microstructures. It confirms the presence of microstructural changes induced by hydrogen, providing critical insights into how hydrogen influences materials at the microscopic level.
- Together, these microscopy techniques offer a comprehensive understanding of macro and microstructural changes in hydrogen-influenced materials, enabling researchers to develop strategies for enhancing material performance in hydrogen-rich environments.

Together, these methodologies are vital for comprehensively understanding the impact of hydrogen on the properties and integrity of metals.

Advanced techniques, such as electron backscatter diffraction (EBSD), further analyse grain orientation and boundaries to understand hydrogen's preferential diffusion paths. Recent developments include:

- Atom Probe Tomography (APT): This technique offers three-dimensional atomic-scale imaging to examine hydrogen clustering in materials, providing insights into hydrogen interactions and phenomena like hydrogen embrittlement.

- In-situ Microscopy: This method enables real-time monitoring of hydrogen's impact during processes such as deformation and phase transitions, helping researchers understand its influence on material behavior.

4. Effects on Mechanical Properties of Ferrous Metals

The absorption of hydrogen adversely impacts the mechanical properties of ferrous metals:

- Ductility and Toughness: Hydrogen embrittlement reduces a metal's ductility, making it more likely to crack under tensile stress, particularly in high-strength steel. This vulnerability can lead to unexpected failures in structural applications.
- Fatigue Resistance: Hydrogen accelerates crack initiation and propagation, significantly lowering a material's fatigue life. This is a critical concern for components exposed to cyclic loading, such as bridges and offshore structures, as it compromises their reliability.
- Hardness and Strength: While hydrogen diffusion can increase localized hardness, it often undermines overall structural integrity. This brittleness can lead to failure under loads that would typically be safe, emphasizing the need to address hydrogen exposure in engineering designs.

The impact varies with factors such as:

- The composition of materials greatly impacts hydrogen behavior in steels, particularly in solubility and diffusivity. Alloying elements like aluminium and silicon help reduce the adverse effects of hydrogen, stabilizing the microstructure and minimizing the risk of hydrogen embrittlement.
- Additionally, fine-grained microstructures provide superior resistance to hydrogen-induced cracking compared to coarse-grained structures. The shorter diffusion paths in fine grains reduce the likelihood of hydrogen accumulation, while their increased strength helps withstand stress better. Thus, selecting appropriate alloying elements and maintaining a fine-grained microstructure can enhance the performance and durability of steels in hydrogen-rich environments.

Additionally:

- Stress Corrosion Cracking (SCC): Hydrogen considerably exacerbates SCC in aqueous environments, presenting significant challenges to the integrity and safety of pipelines and structural components. Understanding the role of hydrogen in SCC is critical for developing effective prevention strategies.
- Thermal Desorption Spectroscopy (TDS): TDS is a sophisticated analytical technique used to measure hydrogen diffusivity and trapping in materials. It offers valuable insights into the behaviour of hydrogen in various metals and alloys, assisting in the assessment of their performance under stress and corrosive conditions. This understanding is essential for mitigating the risk of SCC.

5. Effects on Processing and Fabrication

Hydrogen absorption poses challenges during metal processing and fabrication, particularly welding:

- **Weld Porosity:** During welding, dissolved hydrogen in molten weld pools can form gas bubbles as the material cools, creating porosity. This defect significantly weakens the weld, compromising its structural integrity and reliability, especially in high-load applications.
- **Cold Cracking:** Trapped hydrogen in the weld metal or heat-affected zone (HAZ) can cause delayed cracking, known as hydrogen-induced cracking. This cracking might occur hours or days after welding, making it challenging to detect and prevent. Various factors, including material composition and cooling rates, influence this phenomenon.
- **Reduced Weldability:** The presence of hydrogen complicates the welding process, often requiring pre-heating or post-weld heat treatments to minimize defects. These additional steps lengthen processing times and increase costs, impacting project timelines and budgets.
- **Casting Defects:** In metal casting, hydrogen can create porosity by becoming trapped during solidification. This reduces the load-bearing capacity of cast components, leading to potential premature failure in service. Effective measures, such as managing gas levels and using low-hydrogen alloys, are essential for ensuring the durability of cast products.

To mitigate these issues, industries implement practices such as:

- **Pre-Welding Measures:** Before beginning the welding process, preheat the material to eliminate absorbed hydrogen, and utilize low-hydrogen consumables to reduce the risk of hydrogen introduction into the weld pool.
- **Post-Welding Treatments:** Following the welding process, implement stress-relief annealing to alleviate internal stresses and promote the diffusion of any residual hydrogen from the weld joint.
- **Shielding Gas Control:** During welding, employ argon or helium mixtures as shielding gas to create an inert atmosphere, effectively preventing hydrogen contamination and ensuring a cleaner, stronger weld.

Emerging approaches include:

- **Hybrid Welding Techniques:** This approach combines laser and arc welding to effectively reduce hydrogen contamination. Integrating these methods, enhances control over heat input and stabilizes the weld pool, thereby lowering the risk of hydrogen porosity in the final weld.
- **Additive Manufacturing:** In additive manufacturing, optimizing printing conditions is crucial for minimizing hydrogen trapping in components. Adjusting parameters such as temperature and feed rate allows for a controlled environment, which helps reduce hydrogen absorption and results in stronger, more reliable parts.
- **Simulation Tools:** The use of computational fluid dynamics (CFD) provides valuable predictions regarding hydrogen behavior in weld pools. This modelling offers insights into fluid interactions during welding, enabling engineers to make informed adjustments that further mitigate hydrogen-related challenges in the process.

6. Recommendations and Suggestions for Further Work

To mitigate the challenges associated with hydrogen in metals, the following measures are recommended:

- **Hydrogen Control:**
 - Use effective degassing methods to remove gases during metal melting and casting, ensuring better product quality.
 - Choose low-hydrogen electrodes and fluxes for welding to reduce hydrogen defects.
 - Adjust shielding gas compositions to minimize hydrogen ingress and improve bond quality.
- **Material Design:**
 - Develop and use alloys resistant to hydrogen embrittlement, such as nickel-based superalloys.
 - Apply advanced coatings to reduce hydrogen permeation and protect surfaces.
- **Processing Optimization:**
 - Implement controlled heat treatments to diffuse and release trapped hydrogen effectively.
 - Optimize welding parameters, including current, voltage, and travel speed, to minimize hydrogen absorption.
 - Investigate advanced joining techniques such as friction stir welding, which produce minimal heat-affected zones.
- **Research Directions:**
 - Explore alternative reducing agents with lower reactivity to metals, such as ammonia or bio-based agents.
 - Study advanced diagnostic techniques for real-time hydrogen monitoring, including spectroscopy and in-situ sensors.
 - Investigate hydrogen interactions in advanced materials, such as high-entropy alloys and additive-manufactured metals.
 - Develop predictive models integrating metallurgical principles and machine learning to assess hydrogen's effects.

Conclusion

The utilization of hydrogen as a fuel and reducing agent is pivotal in advancing global sustainability goals by mitigating greenhouse gas emissions. However, the interaction of hydrogen with metals poses challenges, particularly hydrogen absorption, which can result in material embrittlement and a loss of structural integrity.

To combat these issues, it is essential to engage in strategic material selection. High-alloy steels, specific titanium alloys, and advanced composites are preferred due to their inherent resistance to the adverse effects of hydrogen. Additionally, optimizing processing methods—such as controlled fabrication techniques and heat treatments—can further enhance material resilience.

Ongoing research is crucial for the development of new alloys, surface treatments, and protective coatings that effectively reduce hydrogen absorption. Furthermore, the implementation of innovative diagnostic technologies will play a key role in monitoring the integrity of materials in hydrogen environments, allowing for the early detection of potential failures.

By integrating these approaches, we can successfully address the challenges associated with hydrogen absorption, thereby promoting the broader industrial adoption of hydrogen while ensuring the reliability and performance of engineering applications.

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