

Name: - Harsh Patel

Student id: - 2309767

Module Code: - ACEA7010

Subject: - MECHANISMS OF MATERIAL FAILURE

Title: - HYDROGEN EMBRITTLEMEN

Table of Contents

Executive Summary	3
Introduction	3
Literature review	4
Structural Changes Due to Hydrogen Absorption	5
Metallographic Examination	5
Impact on its Mechanical Characteristics	6
Conclusion	9
References.....	11

Executive Summary

This paper considers the opportunities and difficulties presented by hydrogen absorption within metals, considering the effects of this phenomenon on material characteristics and on manufacturing, processing and applications in relation to renewable energy and net zero emission targets. Owing to its role as a sustainable energy carrier hydrogen is being accepted widely, especially for energy production such as through electrolysis. Nevertheless, interaction problems with metals give rise to numerous engineering challenges that require thorough investigation for safeguarding and optimizing its utilization.

Absorption into metals whether in liquid or solid state can lead to severe structural transformation of hydrogen. These changes are porosity, micro voids, and dislocation that reduce the mechanical characteristics of metals, such as strength, ductility, and toughness. This effect has been termed hydrogen embrittlement and is especially more evident in ferrous metals that are used in sensitive operations such as welding or casting. The paper describes how hydrogen impacts metal structures at the sub-microscopic level and overviews ways for diagnosing these alterations using for example optical and electron microscopy.

It also highlights the disadvantage of hydrogen in material processing which includes refining, casting as well as welding. To reduce these effects, some preventive and protective measures such as vacuum degassing, low hydrogen electrodes, and post-weld heat treatment are advised. They also propose that advanced coatings and surface treatments may help to reduce hydrogen aging.

Lastly, the report concludes with a discussion of possible topics for future research which include identifying new materials that can withstand hydrogen interactions, better coatings to protect metals, and further knowledge and understanding of hydrogen behaviors with metal atoms at the nanoscale level. These changes will be instrumental in determining how hydrogen can be safely and efficiently utilized within engineering applications as the world shifts to hydrogen as its main energy source.

Introduction

Hydrogens have been at the forefront of present-day sustainable energy carrier development, the new alternative to fossil fuels, to make the world realize the goals of net zero carbon emissions. And here hydrogen, as both a clean fuel and reducer agent, becomes the primary pillar of an entire renewable energy strategy. Hydrogen can be produced through electrolysis of renewable energy, thus holding a breakthrough in the reduction of carbon footprints in all related industries,

mainly automotive, construction, and energy. There are considerable issues in hydrogen storage and usage due to the unique nature of its chemistry and its physical properties.

Hydrogen in engineering applications presents numerous challenges, and this report delves deeper into a specific aspect: it uses materials' interaction with hydrogen. Going by the report, first, analyzes the origin of hydrogen, the consequence of hydrogen in metallic structures, and the challenges that hydrogen induces in material processing. Structural transformations as a result of hydrogen absorption, chemical evidence, and their effects on mechanical property changes in ferrous metal are the basis for the report to provide an all-inclusive meaning of hydrogen in metallurgical processing. Further, the challenges of hydrogen absorption during fabrication methods, particularly welding, are analyzed.

The main reason, though, is that understanding hydrogen embrittlement becomes very important in engineering since it directly affects material integrity and safety. Hydrogen cracking and reduced mechanical reliability led to catastrophic failure in conditions such as pipelines, storage tanks, and different structural components. Problems like this should become an increasing importance as industries get more embedded into hydrogen-based technologies.

Literature review

Hydrogen is the most abundant element in the universe. Often, hydrogen is found in its combined state. At the molecular level (H_2), hydrogen is a colorless and odorless gas that occasionally is not found together since it is highly reactive. Most hydrogen on this planet exists combined in water (H_2O) or hydrocarbons that act as primary hydrogen sources where they are very abundant in the natural reservoir located in oceans, fossil fuels, and biomass.

Hydrogen production has traditionally been derived from fossil fuels, most notably natural gas reforming, which is responsible for huge emissions of carbon dioxide. However, renewable methods such as electrolysis are increasingly being adopted due to their merits towards environmental conservation. The method of electrolysis demands electricity from renewable sources like solar or wind- to dissolve water molecules into hydrogen and oxygen. The result of this process is "green hydrogen," a carbon-free feedstock that is vital to the net-zero goals. Other methods include biomass gasification and photo electrochemical water splitting, which will help take emission reduction to another level.

Exhaustive studies in the past dealt with hydrogen and its behavior when interacting with materials and especially active metals. The absorption of hydrogen into metallic structures has

usually been demonstrated to result in alteration in their mechanical as well as chemical properties. It has been shown that hydrogen embrittles both ferrous metals and non-ferrous metals, in that absorbed hydrogen causes ductility and strength loss from the metal. Microscopically using optical and electron microscopy, research work on micro structural changes and also defects such as voids, cracks, and dislocations due to hydrogen can be identified.

Structural Changes Due to Hydrogen Absorption

Dissolution of hydrogen in the metals varies di to liquid-solid state, making it a real problem in the processing and performance of the material. Hydrogen dissolves in molten metals at the stages of extraction and casting, mainly due to its small atomic size and high diffusivity. Such situations lead, during cooling and solidification of metals, to the formation of gas

pockets in the molten metals due to the presence of hydrogen. Should the gas find itself trapped within the structure of the solid, the most terrible defect that weakens the mechanical properties of the material is formed? For example, poems caused due to excessive hydrogen when casting aluminum or steel seriously affect a material's fatigue resistance and cause it to fail much more easily under stress. It is during melting that hydrogen can be controlled through melting degassing or inert gas flushing to minimize such desalinate problems.

In the solid state, hydrogen absorption produces more insidious effects on metals. This diffusion and trapping result in the eventual formation of voids and cracks, thus weakening the structural integrity of the metal. Besides, hydrogen makes the metal embrittled in a way that reduces ductility and makes the material fracture suddenly with little stress. These defects become more critical in applications under high stress like pipelines or any structural component because even a slight defect may lead to enormous failure.

It is important for the future development of hydrogen mechanisms from bubble formation in molten metals to defect formation in solid metals.

Metallographic Examination

Metallographic techniques play a significant role in identifying transformation metallurgical hydrogen solutions encountered due to absorption. These techniques are able to give specific qualitative and quasi-quantitative information about the defects and changes resulting from hydrogen in the liquid and solid phases.

Optical Microscopy (OM) is traditionally utilized as the initial method for the investigation of surface and sub-surface defects in metal samples. This method provides visualization of pores,

cracks, and voids arising from hydrogen diffusion using light. For example, during the steel or aluminum alloy casting process, hydrogen-induced porosity can be detected by OM, under which it looks as small and irregular pores in the microstructure. Admittedly, OM represents a simple and effective method to detect and measure surface irregularities, and yet it is not very efficient when it comes to examining smaller subsurface modifications.

To surmount this limitation, Electron Microscopy (EM) is used. Hydrogen-induced resistant Steels, SEM provides high resolution for the identification of hydrogen-related damages such as micro voids, crack formation, and transformation in grain boundaries. Transmission Electron Microscopy (TEM) went further into the atomic levels showing dislocations and distorted lattices induced by hydrogen trapping. TEM can detect specific hydrogen-induced features which include nodes which is formed in some hydrogen-sensitive metals such as titanium.

Results Interpretation: Metallographic evidence repeatedly shows that metal structures change with hydrogen absorption. For instance, characterization utilizing an SEM of high-strength steel may reveal interactions such as micro cracking which begins at the grain boundary hydrogen embrittlement. Likewise, TEM analysis can shed light on how hydrogen embrittlement affects dislocation pile-ups and spatial distribution that occur due to the diffusion of hydrogen. These structural modifications have been found to exhibit significant negative relationships with mechanical properties such as tensile strength, ductility, and fatigue resistance.

By employing OM and EM, the following insights about hydrogen behavior on metals are achieved by researchers. Thus, such knowledge is crucial and helps to design materials based on which to prevent hydrogen-caused degradation, reliability, and safety in hydrogen-oriented applications.

Impact on its Mechanical Characteristics

It influences the mechanical characteristics of ferrous metals in a very significant manner to the extent that such alloys cannot always deliver the required performance in important applications. The most significant changes are registered in strength, ductility, toughness, and hardness.

However, concerning ductility and toughness, hydrogen embrittlement is a critical issue. When hydrogen penetrates distribution into ferrous metals, it retards their capacity to deform plastically thus becoming brittle and will fail suddenly. This is particularly so in high-strength steels where even comparatively very low concentrations of hydrogen can cause severe cracking under stress. The tolerance to energy before failure similarly reduces significantly once microvoids and cracks develop as a result of the release of hydrogen.

The strength and hardness may be changed in some intricate ways. Even though hardness is temporarily enhanced by hydrogen absorption via localized lattice distortions, hydrogen reduces

total strength due to the aggregation of structural imperfections. This dual influence distorts the execution and usage of ferrous metals in hydrogen-intense conditions including pipelines and storage tanks.

Material Behavior under Different Conditions: The behavior of ferrous metals under different circumstances also underlines the difficulties of hydrogen pick-up. While the material undergoes strength enhancement at high temperatures, the rate of hydrogen diffusion increases leading to embrittlement and cracking. These features of the behavior of hydrogen in iron and steel lead to a sharp reduction of fatigue resistance under cyclic loading when cracks originate at an early stage and progress rapidly. On the other hand, the diffusion process may be slower at low temperatures while brittleness increases and causes sudden failures in cryogenic service.

In general, the impact of hydrogen on mechanical properties points to the precautionous need for material selection and treatment. Thus, understanding how hydrogen changes the properties of ferrous metals in various conditions is crucial for the safety and reliability of hydrogen materials and structures which is especially important for hydrogen utilization in energy production transition.

Cognitive Influence on Processing and Fabrication

This paper sought to establish how hydrogen affected the processing and fabrication efficiency of metals and the quality of the final product. Regarding heat treatment, hydrogen absorption may cause defects in the material at every stage – from refining to casting and welding that reduce its performance, which makes management of the phenomenon a major concern in material science.

Hydrogen in Processing: In every refining and casting process, hydrogen easily gets in the molten metals and some problems such as porosity and voids occur when the metal is cooling down or has solidified. For instance, in aluminum for casting, the extra volume of hydrogen causes the formation of loose bubbles which are retained, reducing the metal's mechanical strength. In the same manner, in steel production, when the metal is refined, it dissolves hydrogen, which results in hydrogen pickup and consequently decreases the ductility and strength of the material. These problems are solved with the help of such preventive measures as vacuum degassing, the use of inert gases, and controlling furnace atmospheres. These methods reduce how the hydrogen can act on the molten metals and thus provide better structural strength.

Welding: Another issue is related to hydrogen usage in fabrication, especially when welding. The hydrogen can come from moisture, and flux, used in welding or from the environment air during the process of welding. This can lead to hydrogen-induced cracking, known also as cold

cracking which usually occurs after the weld has cooled. Challenging high-strength steels are particularly susceptible, as the quenching hydrogen gets locked into the solidifying weld metal, opposing localized stress and crack inception sites.

To counter these risks, preheat, post-weld heat treatment, and low hydrogen electrodes are used in the construction of structures. The benefits of preheating are slowing down the rate at which the hydrogen penetrates through the material, while with the help of post-weld heat treatment, the hydrogen trapped in the steel material is allowed to come out reducing the weld residual stresses. Minimizing hydrogen pick-up liability through proper storage of welding consumables and adequate control of working environment humidity in addition helps in minimizing other related liabilities.

Through consideration of the present work, manufacturers shall be in a better position to address hydrogen effects of processing and fabrication hence improving the material properties and reliability of fabricated components for safer use in hydrogen-rich systems.

Recommendations and Further Research

It is of paramount importance for materials that will be used in industrial hydrogen environments to eliminate or better control hydrogen absorption during production, and fabrication processes. Preventative measures, new materials, and more research on hydrogen- related problems and uses will lessen hydrogen-induced problems while expanding engineering uses.

Strategies to Reduce Hydrogen Absorption:

Whereas, in other production processes, much tighter controls of the environment greatly reduce the amount of hydrogen that can be absorbed. Some measures like during the refining process, use of vacuum degassing, and during casting use of inert gas also assist in the removal of hydrogen and checking for any re-absorption. Some of the critical activities that need to be followed include the use of low-hydrogen electrodes with the consumable stored properly in a dry environment, preheating, post-weld heat treatment and the like. Also, using of various special coating or surface treatments can serve as a barrier and stop hydrogen from penetrating into metallic parts.

Future Research Directions:

The mitigation of hydrogen embrittlement is another interesting field to invest in; scientists should therefore focus on creating better measurements of sophisticated alloys. For instance, the microstructure of high entropic alloys and nanostructure materials has indicated the ability to

reduce hydrogen impact. In the same way, research into new coating technologies, which may include ceramic, or so-called grapheme coatings could help improve the protection against hydrogen diffusion.

More research was also conducted to understand the interface chemistry of hydrogen with metals at an atomic level. Improved instruments for simulation and real-time measurements, including in-situ electron microscopy, could give more understanding of hydrogen-induced micro structural evolutions. Other related research areas that could be of great value include exploring other sustainable production processes, including hydrogen-friendly additive manufacturing processes.

With the help of these strategies and through focused research industries can come up with better materials for hydrogen related sectors that are more resistant to all kinds of degradations. These efforts will underpin the sustainable development of renewable energy systems and hydrogen, of particular importance to the integration of hydrogen into key engineering systems.

Conclusion

Remarkably, hydrogen is at the same time a clean energy storage medium and a promising reluctant for industries in the process of renewing energy resources. However, it exposes intimate atomic size effective for strong chemical reactivity and some unusual metal interactions constituting difficulties in material processing and manufacturing.

The report provides the background as to how hydrogen exists in its pure form and when produced from renewable power sources such as electrolysis that serve the goal of net-zero energy strategies. Nonetheless, its solubility in metals in both liquid and solid forms plays a role in straining the metals including porosity changes, micro voids, and dislocations that are detrimental to metal strength, ductility, and toughness. Together, these effects are called hydrogen embrittlement and they pose significant consequences to the reliability and serviceability of ferrous metals, particularly under mechanical stressed services.

The microstructure analysis showed a quantitative depiction of the hydrogen exposure effect through metallographic investigation coupled analyzed with optical and electron microscope to show the structural surface damage due to hydrogen soaked. Additionally, its involvement in processing and fabrication especially during the refining, casting, and welding processes

underlines the significance of proper preventive measures prevention as well as control measures in the prevention of material failure.

In the future, properly developing methods of vacuum degassing, advanced coatings and heat treatment protocols can help to minimize hydrogen-related problems. New generation high-temperature alloys and functional coatings, combined with the improved understanding of hydrogen metal interactions will be imperative to prevail over these said challenges.

While hydrogen is being used in more systems and manufacturing processes, its benefits as a green fuel will need to be weighed against its disadvantages as a material science problem. By solving these issues, the engineering community opens the path to the creation of safer and more resilient materials that answer the vision of a green future where hydrogen fuel is dominant.

References

Laadel, N. E., El Mansori, M., Kang, N., Marlin, S., & Boussant-Roux, Y. (2022). Permeation barriers for hydrogen embrittlement prevention in metals—a review on mechanisms, materials suitability and efficiency. *International Journal of Hydrogen Energy*, 47(76), 32707-32731. <https://doi.org/10.1016/j.ijhydene.2022.07.164>

Choudhary, S., Vishwakarma, M., & Dwivedi, S. K. (2021). Evaluation and prevention of hydrogen embrittlement by NDT methods: a review. *Materials Proceedings*, 6(1), 18. <https://doi.org/10.3390/CMDWC2021-10044>

Li, X., Yin, J., Zhang, J., Wang, Y., Song, X., Zhang, Y., & Ren, X. (2022). Hydrogen embrittlement and failure mechanisms of multi-principal element alloys: A review. *Journal of Materials Science & Technology*, 122, 20-32. <https://doi.org/10.1016/j.jmst.2022.01.008>

Van Der Schijff, O. J., Budiansky, N., & Latanision, R. M. (2021). Hydrogen Damage and Embrittlement. In *Failure Analysis and Prevention* (pp. 518-532). ASM International. <https://doi.org/10.31399/asm.hb.v11.a0006784>

Wetegrove, M., Duarte, M. J., Taube, K., Rohloff, M., Gopalan, H., Scheu, C., ... & Kruth, A. (2023). Preventing hydrogen embrittlement: the role of barrier coatings for the hydrogen economy. *Hydrogen*, 4(2), 307-322. <https://doi.org/10.3390/hydrogen4020022>

Giannini, L., Razavi, N., Alvaro, A. *et al.* Embrittlement, degradation, and loss prevention of hydrogen pipelines. *MRS Bulletin* **49**, 464–477 (2024). <https://doi.org/10.1557/s43577-024-00695-9>

Campari, A., Ustolin, F., Alvaro, A., & Paltrinieri, N. (2023). A review on hydrogen embrittlement and risk-based inspection of hydrogen technologies. *international journal of hydrogen energy*, 48(90), 35316-35346. <https://doi.org/10.1016/j.ijhydene.2023.05.293>

Chen, Y., Zhao, S., Ma, H., Wang, H., Hua, L., & Fu, S. (2021). Analysis of hydrogen embrittlement on aluminum alloys for vehicle-mounted hydrogen storage tanks: A review. *Metals*, 11(8), 1303. <https://doi.org/10.3390/met11081303>

