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Hydrogen Embrittlement Behavior and Mitigation Strategies in Metallic Materials

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Abstract

Hydrogen embrittlement (HE) remains a critical challenge in the reliability and safety of metallic components across a range of engineering applications, from aerospace to energy infrastructure. This review comprehensively explores the fundamental mechanisms underlying HE—including hydrogen-enhanced decohesion (HEDE), hydrogen-enhanced localized plasticity (HELP), and hydride-induced embrittlement—across various metal systems. Emphasis is placed on advanced characterization techniques such as thermal desorption spectroscopy, atom probe tomography, and in-situ mechanical testing, which provide multi-scale insights into hydrogen transport, trapping, and damage evolution. The study further evaluates key factors influencing HE susceptibility, including alloy composition, microstructural features, environmental conditions, and applied stress states. Mitigation strategies are systematically discussed, focusing on alloy design, microstructural engineering, surface treatments, and thermal processing. By integrating mechanistic understanding with practical prevention methods, this work provides a comprehensive framework for the design and maintenance of hydrogen-tolerant metallic materials in modern engineering systems.

Keywords: Hydrogen Embrittlement; Metallic Components; Hydrogen-Enhanced Decohesion; Hydrogen-Enhanced Localized Plasticity; Hydride-Induced Embrittlement; Metallic Materials

1 INTRODUCTION

Hydrogen embrittlement has been recognized as a degradation phenomenon for over a century, yet it remains one of the least understood forms of material failure. In metallic systems, hydrogen can be introduced during manufacturing processes such as welding, electroplating, and pickling, or during service through corrosion reactions and hydrogen-containing environments. Once absorbed, hydrogen interacts with lattice defects, segregates at grain boundaries, and accumulates in areas of high stress concentration, ultimately leading to embrittlement, loss of ductility, and fracture without significant macroscopic deformation.

The global energy landscape has been shifting toward hydrogen as a clean and sustainable fuel. This transition brings about increasing demand for structural materials that can withstand hydrogen-rich environments without suffering from embrittlement. Understanding the fundamental mechanisms behind hydrogen embrittlement is therefore of critical importance for the development of next-generation materials and for ensuring structural integrity in hydrogen-based technologies. Furthermore, as new classes of high-strength and nanostructured alloys are being developed to meet the demands of advanced engineering systems, the interplay between microstructure and hydrogen susceptibility becomes an urgent area of research. This necessitates not only a thorough exploration of the mechanistic origins of HE but also the formulation of practical and scalable mitigation strategies that can be applied across diverse industrial sectors.

2 MECHANISMS OF HYDROGEN EMBRITTLEMENT

2.1 Hydrogen-Enhanced Decohesion (HEDE)

The hydrogen-enhanced decohesion (HEDE) mechanism posits that the presence of hydrogen at specific interfaces—such as grain boundaries, phase boundaries, or cleavage planes—reduces the cohesive strength of metallic bonds,

thereby promoting intergranular or transgranular fracture. According to this model, hydrogen atoms segregate preferentially to sites of high hydrostatic stress or lattice dilation, where they weaken atomic bonding by altering the electronic structure of the host metal. First-principles calculations and molecular dynamics simulations have provided theoretical support for this phenomenon, indicating that hydrogen can reduce the work of separation at critical interfaces.

Experimental evidence for HEDE has been observed in several high-strength steels and nickel-based alloys, where brittle fracture features correlate with hydrogen segregation. Notably, fracture surfaces often exhibit intergranular morphology in the presence of hydrogen, even in materials that typically fail in a ductile mode. The HEDE model is particularly relevant in scenarios where diffusion-limited hydrogen transport leads to local saturation at critical interfaces under tensile stress, triggering rapid and catastrophic failure. However, the challenge in isolating decohesion events from other concurrent mechanisms complicates the direct validation of this theory[1].

2.2 Hydrogen-Enhanced Localized Plasticity (HELP)

In contrast to HEDE, the hydrogen-enhanced localized plasticity (HELP) mechanism asserts that hydrogen promotes dislocation motion and enhances local plastic deformation rather than directly weakening atomic bonds. The presence of hydrogen is believed to lower the energy barriers for dislocation nucleation and glide, thereby facilitating highly localized plastic flow. This localized deformation can lead to microvoid coalescence, strain localization, and eventual crack initiation and propagation.

Transmission electron microscopy (TEM) studies have shown increased dislocation density and planar slip in hydrogen-exposed specimens, lending strong experimental support to the HELP model. Additionally, in situ nanoindentation and micro-cantilever bending tests have revealed pronounced softening effects in hydrogen-charged regions. The HELP mechanism is particularly relevant in materials such as austenitic stainless steels and certain aluminum alloys, where hydrogen does not induce hydride formation yet markedly influences mechanical response. Although HELP-driven plasticity can delay fracture in some cases, it often results in high strain localization at crack tips, leading to premature failure under cyclic or sustained loading.

2.3 Hydride Formation and Embrittlement

In certain hydrogen-sensitive metals, such as titanium, zirconium, and vanadium, the embrittlement process is strongly associated with the formation of brittle hydride phases. These hydrides precipitate when hydrogen concentration exceeds the solubility limit in the host matrix, typically at low temperatures or under high hydrogen pressures. The hydride phases generally possess a different crystal structure and significantly lower ductility compared to the base metal, thereby acting as stress concentrators and crack initiators.

Hydride-induced embrittlement is typically characterized by transgranular cleavage fracture, often aligned with specific crystallographic planes of the hydride phase. The orientation, size, and distribution of hydrides are critical factors governing fracture behavior. For instance, needle-like hydrides aligned perpendicular to the loading direction can significantly reduce fracture toughness. The transformation-induced volumetric expansion accompanying hydride precipitation also contributes to internal stresses, further exacerbating crack initiation and propagation. Control of hydrogen ingress, phase stability, and microstructural design are thus crucial in mitigating hydride-related embrittlement in susceptible alloy systems[2].

2.4 Synergistic and Competing Mechanisms

While individual models such as HEDE, HELP, and hydride formation offer valuable insights, real-world hydrogen embrittlement phenomena often involve the interplay of multiple mechanisms acting simultaneously or sequentially. For example, hydrogen-induced dislocation motion (HELP) may enhance local plastic strain, promoting decohesion at interfaces (HEDE), particularly in high-strength steels where both mechanisms are operative. Similarly, localized plasticity can facilitate hydrogen accumulation at microstructural defects, initiating hydride precipitation in susceptible alloys.

The competition and synergy among these mechanisms depend strongly on the material system, hydrogen

concentration, strain rate, temperature, and microstructural state. For instance, in nanostructured materials with high density of grain boundaries and dislocations, the diffusivity and trapping of hydrogen may alter the relative dominance of HEDE versus HELP. Understanding these interactions requires integrated experimental – computational approaches, including in situ mechanical testing, atomistic simulations, and advanced characterization techniques such as APT (atom probe tomography) and EBSD (electron backscatter diffraction).

Developing a unified framework for hydrogen embrittlement mechanisms remains an ongoing challenge. Future research must aim to bridge the gap between atomic-scale interactions and macroscopic fracture behavior, with emphasis on quantifying the transition thresholds between competing mechanisms and identifying dominant pathways under service-relevant conditions.

3 CHARACTERIZATION AND DETECTION TECHNIQUES

3.1 Electrochemical Permeation and Thermal Desorption Spectroscopy (TDS)

Electrochemical hydrogen permeation and thermal desorption spectroscopy (TDS) are among the most widely used techniques for studying hydrogen ingress, trapping behavior, and diffusivity in metals. In electrochemical permeation experiments, hydrogen is generated on one side of a metallic membrane via cathodic polarization and monitored on the opposite side as it permeates through the material. This approach allows for the determination of effective diffusion coefficients, apparent hydrogen solubility, and trap site characteristics. The technique is particularly valuable for comparing the hydrogen transport behavior of different alloy systems and for assessing the impact of surface treatments, coatings, and microstructural modifications[3].

TDS complements permeation methods by providing insights into the binding energies and kinetics of hydrogen traps within the microstructure. In a TDS experiment, hydrogen-charged specimens are subjected to a controlled heating process under vacuum, during which desorbed hydrogen is quantitatively measured as a function of temperature. This enables the identification of reversible and irreversible trapping sites such as dislocations, grain boundaries, second-phase particles, and vacancies. TDS spectra often reveal multiple peaks corresponding to different trapping energies, offering a window into the interaction between hydrogen and microstructural heterogeneities. However, due to its bulk-averaging nature and lack of spatial resolution, TDS must often be used in conjunction with microscopy techniques for a complete interpretation.

3.2 Atom Probe Tomography (APT) and Transmission Electron Microscopy (TEM) Analysis

Atom probe tomography (APT) and transmission electron microscopy (TEM) provide high-resolution structural and chemical insights into hydrogen-related phenomena at the nanoscale. APT, in particular, is uniquely capable of detecting hydrogen atoms directly and mapping their three-dimensional distribution with near-atomic resolution. This technique has enabled the visualization of hydrogen segregation at grain boundaries, phase interfaces, and dislocation cores, thereby providing critical evidence in support of theoretical embrittlement models such as HEDE and HELP. Recent advancements in cryo-preparation and controlled charging protocols have improved the reliability of hydrogen detection in APT, although quantification remains challenging due to background hydrogen and ion trajectory artifacts.

TEM offers unparalleled imaging resolution and is indispensable for characterizing hydrogen-induced microstructural changes such as dislocation structures, phase transformations, and void formation. In-situ TEM, combined with environmental or hydrogen-charging capabilities, allows for the direct observation of dislocation dynamics, crack initiation, and hydride precipitation under applied stress. High-angle annular dark-field (HAADF) imaging, energy-dispersive X-ray spectroscopy (EDS), and electron energy loss spectroscopy (EELS) further enable compositional and bonding analysis at the nanoscale. While TEM does not detect hydrogen atoms directly, its strength lies in correlating deformation behavior and damage evolution with local microstructure in hydrogen-exposed samples[4].

3.3 In-Situ Mechanical Testing with Hydrogen Charging

In-situ mechanical testing under hydrogen-charging conditions represents a powerful approach to studying hydrogen embrittlement in real time and under service-relevant environments. These experiments typically involve tensile, fatigue, or fracture toughness testing within a custom-built chamber that allows simultaneous hydrogen charging, either electrochemically or through high-pressure gas exposure. The primary advantage of this method lies in its ability to capture the dynamic interaction between mechanical loading and hydrogen-induced damage accumulation.

This technique has been particularly effective in revealing time-dependent effects such as hydrogen-enhanced crack growth rates, delayed failure under constant load, and sensitivity to strain rate and stress intensity. Digital image correlation (DIC), acoustic emission monitoring, and optical or electron microscopy can be integrated with in-situ setups to provide spatially resolved strain and crack propagation data. Recent developments in synchrotron X-ray diffraction and tomography have further expanded the capabilities of in-situ testing by enabling three-dimensional mapping of strain fields, phase evolution, and void formation in hydrogen-charged specimens[5]. These multi-modal approaches offer a more comprehensive picture of embrittlement behavior but require careful control of experimental parameters to ensure reproducibility and meaningful interpretation.

3.4 Fractographic Analysis and Crack Propagation Monitoring

Fractographic analysis remains an essential post-mortem technique for diagnosing hydrogen embrittlement and distinguishing it from other failure mechanisms. Scanning electron microscopy (SEM) is widely employed to examine fracture surfaces at high magnification, revealing characteristic features such as intergranular cleavage, quasi-cleavage facets, secondary cracks, and microvoids. In hydrogen-embrittled samples, fracture surfaces often exhibit brittle morphology even when the macroscopic stress-strain response appears ductile, emphasizing the importance of detailed surface analysis.

Quantitative fractography can be coupled with crack growth rate measurements to assess the influence of hydrogen on fatigue and stress corrosion cracking behavior. Methods such as compliance measurement, direct current potential drop (DCPD), and digital image correlation (DIC) are frequently used to monitor crack propagation in real time under controlled hydrogen exposure. These measurements provide critical data for life prediction models and structural integrity assessments. Furthermore, fractographic evidence often correlates with the operative embrittlement mechanism—intergranular fracture suggests HEDE, while dimpled rupture with planar slip traces may indicate HELP-related localization.

In sum, a holistic understanding of hydrogen embrittlement requires a multi-technique approach, integrating global and local methods that span different length and time scales. Each technique offers unique insights, and their synergistic application is essential for unraveling the complex interplay between hydrogen, microstructure, and mechanical response.

4 INFLUENCING FACTORS OF HYDROGEN EMBRITTLEMENT

4.1 Material Composition and Microstructure

The chemical composition of a metallic alloy plays a decisive role in determining its susceptibility to hydrogen embrittlement. Different alloying elements influence hydrogen solubility, diffusivity, and trap density, as well as microstructural evolution during processing and service. For example, carbon, phosphorus, and sulfur are known to segregate grain boundaries and enhance intergranular embrittlement by facilitating hydrogen trapping and decohesion. In contrast, elements such as chromium, molybdenum, and nickel can improve resistance by promoting passive film formation or altering trap energetics.

Microstructure exerts a profound influence on hydrogen behavior at multiple scales. Fine-grained structures generally exhibit higher resistance to crack propagation due to enhanced toughness and increased boundary density, which can act as hydrogen traps that impede diffusion. However, under certain conditions, such as in ultra-fine-grained or nanostructured materials, the large density of interfaces may act as pathways for accelerated hydrogen transport. The distribution, size, and morphology of second-phase particles and intermetallics also affect hydrogen distribution, often serving as either reversible or irreversible traps depending on their coherency and

interface energy[6]. Martensitic and bainitic phases in high-strength steels are particularly prone to embrittlement due to high internal stresses and dislocation density, which enhance hydrogen trapping and localization of plasticity.

4.2 Grain Boundaries, Precipitates, and Dislocations

Grain boundaries, precipitates, and dislocations serve as key microstructural features that control hydrogen trapping, accumulation, and interaction with applied stress fields. Grain boundaries, especially high-angle ones, act as both preferential trapping sites and potential fracture paths due to their relatively high energy and disrupted lattice structure. Hydrogen segregation at these boundaries can significantly reduce cohesive strength, thereby promoting intergranular fracture modes associated with the HEDE mechanism.

Precipitates, depending on their size, composition, and coherency, can either mitigate or exacerbate hydrogen embrittlement. Coherent nanoscale precipitates may act as benign reversible traps, whereas incoherent or semi-coherent precipitates with high misfit strain often induce localized stress concentrations that facilitate crack nucleation. Carbides, nitrides, and sulfides are particularly relevant in steels and nickel-based alloys, where they can create stress intensification zones conducive to hydrogen-assisted crack growth.

Dislocations, due to their strain fields and associated lattice distortions, are highly effective hydrogen traps. They facilitate localized plasticity by acting as pathways for hydrogen-enhanced dislocation mobility, a key feature of the HELP mechanism. Dislocation networks and pile-ups, especially near crack tips or hard phase boundaries, promote hydrogen accumulation and strain localization. The interplay between dislocation density and hydrogen diffusion kinetics determines the spatial distribution of embrittlement susceptibility within a component. Moreover, dynamic interactions such as hydrogen-enhanced cross-slip or climb can further alter deformation mechanisms under service conditions.

4.3 Environmental Conditions (Temperature, Pressure, pH)

Environmental variables such as temperature, hydrogen partial pressure, and electrolyte pH significantly modulate the kinetics of hydrogen absorption, diffusion, and trapping, thereby altering the embrittlement response of metallic materials. Temperature influences hydrogen solubility and mobility in the matrix; higher temperatures generally increase diffusivity but may also reduce solubility, depending on the alloy system. At low temperatures, hydride formation becomes favorable in susceptible alloys like titanium and zirconium, leading to brittle fracture via precipitation-induced embrittlement.

Hydrogen partial pressure governs the chemical potential and driving force for hydrogen ingress. Under high-pressure gaseous environments, such as in hydrogen transport or storage systems, the increased fugacity can lead to elevated bulk hydrogen concentrations, even in materials with otherwise low permeability. This scenario often accelerates time-dependent cracking phenomena such as hydrogen-induced delayed fracture or stress corrosion cracking[7].

The pH of the environment affects both hydrogen generation kinetics and surface stability. In acidic media, particularly under cathodic polarization, hydrogen evolution reactions (HER) are more vigorous, resulting in rapid hydrogen uptake. Alkaline environments may favor the formation of protective oxide films, which can act as kinetic barriers to hydrogen ingress, though film breakdown under mechanical or electrochemical stimuli can still initiate embrittlement. The presence of aggressive ions such as chlorides or sulfides can further destabilize passive films and promote localized corrosion, enhancing the susceptibility to hydrogen-assisted cracking.

4.4 Loading Conditions and Stress States

The mechanical loading conditions, including stress magnitude, loading rate, and stress state (uniaxial, multiaxial, or triaxial), critically influence hydrogen embrittlement behavior. Tensile stresses, particularly those with high triaxiality at crack tips or notches, provide a thermodynamic driving force for hydrogen diffusion and trapping. These stress concentrations enhance hydrogen transport to critical sites and facilitate crack initiation, especially in materials with pre-existing microstructural traps or surface flaws.

Loading rate is another vital factor. Slow strain rates allow more time for hydrogen to diffuse to regions of stress concentration, often resulting in more severe embrittlement due to enhanced localization of damage. Conversely, at very high strain rates, hydrogen may not have sufficient time to migrate to the fracture zone, and thus embrittlement effects may be suppressed or delayed. This time-dependence is particularly evident in delayed fracture or sustained-load cracking in high-strength steels and titanium alloys.

Cyclic loading conditions, as encountered in fatigue and corrosion-fatigue environments, further exacerbate embrittlement by promoting the progressive accumulation of hydrogen at crack tips and the formation of microvoids or secondary cracks. The coupling between mechanical cycling and hydrogen diffusion can significantly accelerate crack growth rates, especially under cathodic protection or corrosive environments. Understanding the synergy between loading history and hydrogen kinetics is therefore essential for developing accurate life prediction models and failure prevention strategies in hydrogen-sensitive components.

5 MITIGATION AND PREVENTION STRATEGIES

5.1 Alloy Design and Microstructural Engineering

Alloy design is one of the most fundamental strategies for controlling hydrogen embrittlement, offering the ability to tune hydrogen solubility, diffusion, and trapping behavior through composition and microstructural manipulation. The selection and optimization of alloying elements directly influence phase stability, dislocation density, and trap site distributions. For example, in high-strength steels, the addition of elements such as Ni, Cr, and Mo can improve resistance by refining microstructure, promoting protective oxide formation, and stabilizing austenite, which generally exhibits lower susceptibility to hydrogen-assisted cracking compared to ferritic or martensitic phases.

Advanced alloy design strategies often aim to introduce controlled hydrogen traps that immobilize hydrogen without facilitating crack initiation. These “benign” traps, such as finely dispersed coherent carbides or nitrides, can effectively sequester diffusible hydrogen, reducing its availability at high-stress locations. Simultaneously, the elimination or reduction of “harmful” traps—such as coarse, incoherent inclusions or brittle second phases—is critical to avoid premature cracking[8].

Recent developments in computational thermodynamics and high-throughput alloy screening have enabled the design of compositionally complex alloys (e.g., high-entropy alloys and medium-entropy steels) with superior resistance to hydrogen embrittlement. These systems often combine sluggish diffusion kinetics, stable face-centered cubic (FCC) phases, and a high density of low-energy interfaces that suppress crack propagation. Tailoring grain size, texture, and phase distribution through thermo-mechanical processing further enhances resistance by altering hydrogen pathways and toughening the matrix.

5.2 Surface Treatment and Coating Technologies

Surface engineering plays a pivotal role in mitigating hydrogen ingress, as the material-environment interface is the primary locus for hydrogen generation and absorption. Surface treatments and coatings can serve multiple functions: forming diffusion barriers, altering surface chemistry, modifying residual stress profiles, or enhancing corrosion resistance.

Coating technologies such as physical vapor deposition (PVD), chemical vapor deposition (CVD), and thermal spraying have been widely employed to deposit hydrogen-impermeable films. Ceramic-based coatings, including alumina, zirconia, and titanium nitride, exhibit excellent resistance to hydrogen permeation and are chemically stable under harsh conditions. Similarly, metallic coatings such as nickel or chromium layers can serve as sacrificial barriers, though care must be taken to prevent microcrack formation or galvanic interactions that may accelerate local hydrogen entry.

Surface treatments such as shot peening, laser shock peening, and low plasticity burnishing introduce beneficial compressive residual stresses in the near-surface region, which act to counteract tensile stress-driven hydrogen diffusion and retard crack initiation. Additionally, nitriding and carburizing processes not only harden the surface but can also form nitride or carbide networks that act as microstructural traps, decreasing hydrogen diffusivity.

Emerging strategies include the use of self-healing coatings, multifunctional oxide films, and nanostructured surface layers designed to dynamically adapt to environmental changes. The durability, adhesion, and integrity of such coatings under cyclic mechanical loading and thermal fluctuations remain critical challenges for implementation in structural components.

5.3 Heat Treatment and Thermal Cycling Strategies

Heat treatment is a well-established technique for tailoring microstructures and relieving internal stresses, both of which are central to hydrogen embrittlement resistance. Controlled thermal treatments can modify phase morphology, redistribute solute atoms, and anneal out harmful defects such as vacancy clusters or dislocation tangles that serve as hydrogen traps.

Annealing treatments, particularly in the sub-critical or intercritical regimes, can reduce residual tensile stresses introduced during welding, machining, or cold forming. Stress relief annealing helps to homogenize the microstructure and eliminate hydrogen concentration gradients, thereby stabilizing the material against delayed cracking. Solution heat treatment followed by appropriate aging or tempering can also enhance resistance by optimizing precipitate characteristics and controlling retained austenite content.

Thermal cycling strategies, where materials are subjected to repeated controlled heating and cooling, can further improve hydrogen tolerance by inducing phase transformation toughening or by redistributing hydrogen to benign traps. This approach is particularly effective in multi-phase alloys such as dual-phase steels and maraging steels, where phase boundaries and interfaces can be engineered to deflect or blunt cracks.

However, the efficacy of thermal treatments is highly dependent on material chemistry and prior processing history. Over-aging or excessive annealing can lead to grain coarsening, reduced strength, or the formation of embrittlement-prone phases. As such, precise process control and integration with alloy design are essential for optimizing hydrogen resistance via thermal strategies.

5.4 Cathodic Protection and Electrochemical Control

Cathodic protection is commonly employed to mitigate corrosion-driven hydrogen ingress, particularly in marine, pipeline, and offshore applications. This technique involves applying a negative potential to the metal surface, effectively converting it into a cathode and thereby suppressing anodic dissolution. While effective in preventing general corrosion, improper cathodic polarization can paradoxically promote hydrogen evolution reactions (HER) and increase the risk of hydrogen embrittlement, especially in high-strength materials.

Electrochemical control strategies must therefore balance the protective benefits of cathodic polarization with the risk of excessive hydrogen generation. Optimizing the potential window is critical: potentials that are too negative can significantly accelerate hydrogen absorption, while those that are insufficient may fail to prevent corrosion. The use of reference electrodes, monitoring systems, and intelligent control algorithms is essential to maintain protection within the “safe” potential range.

Sacrificial anodes (e.g., magnesium, zinc) and impressed current systems are two common cathodic protection methods, each with their own advantages and limitations in terms of effectiveness, cost, and maintenance. In environments with mixed oxidizing and reducing species, combined protection schemes may be needed to avoid localized corrosion or pitting that can act as hydrogen entry points.

Advanced electrochemical approaches, including potential pulsing and anodic polarization for film regeneration, are being explored to mitigate hydrogen uptake while maintaining surface passivity. Moreover, the integration of corrosion inhibitors and environment conditioning—such as pH buffering and deoxygenation—can further suppress HER kinetics and minimize embrittlement risks.

6 CONCLUSION

Hydrogen embrittlement presents a complex, multi-mechanistic phenomenon that severely compromises the mechanical integrity of metals under hydrogen exposure. The interplay between hydrogen diffusion, microstructural

traps, and external stressors leads to a spectrum of failure modes that vary with alloy type, environment, and loading conditions. Mechanistic models such as HEDE, HELP, and hydride formation provide essential, albeit not mutually exclusive, frameworks for interpreting embrittlement behavior across different materials. Advanced characterization tools have significantly improved our ability to visualize and quantify hydrogen-microstructure interactions, enabling more accurate predictions of material performance.

Effective mitigation requires a holistic approach, combining tailored alloy design, microstructural control, surface modification, and environmental management. Emerging materials like high-entropy alloys and advanced coating technologies offer promising avenues for future development. Nonetheless, the challenge of HE persists, particularly under cyclic loading and in aggressive service environments. Ongoing research should aim to unify theoretical models, enhance detection sensitivity at the atomic scale, and develop predictive lifetime models. Through interdisciplinary efforts spanning materials science, mechanical engineering, and electrochemistry, the long-standing challenge of hydrogen embrittlement can be more effectively addressed, ensuring safer and more durable metallic systems in hydrogen-rich applications.

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