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Abstract

Hydrogen embrittlement of steel is defined as a deterioration in the mechanical properties of a metal due to stress corrosion cracking. This process typically begins with crack formation and progresses to fracture due to decreased ductility and increased brittleness. This undermines the reliability of these metals in industries such as automotive, oil and gas, and construction, which rely heavily on steel structures. This process has been studied in numerous scientific studies, but its understanding remains uneven. To address this problem, it is first necessary to understand the underlying mechanisms and factors affecting hydrogen brittleness. This paper aims to review the literature and publications related to hydrogen brittleness on high-strength steel and its impact on steel pipes used in aqueous environments. The paper focuses on recent developments and methods that have contributed to a better understanding of the relationship between steel structure, properties, and performance, with a particular focus on the factors that cause and affect hydrogen brittleness.

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KeyWords: Hydrogen Embrittlement, High-Strength Steel, Steel Pipeline, HEE, HPT, HELP, AIDE.

تلف التقصف الهيدروجيني في الفولاذ عالي المقاومة لخطوط أنابيب الغاز الطبيعي في البيئات المائية

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الملخص:

تقصّف الفولاذ الناتج عن الهيدروجين هو تدهور في الخصائص الميكانيكية للمعدن بسبب تأثيرات الإجهاد والتآكل المرتبطة بوجود الهيدروجين. حيث تتكوّن شقوق دقيقة بداية داخل البنية المعدن، ثم تتطور تدريجيًا لكسر بسبب انخفاض الليونة وازدياد الهشاشة. مما يقلل بشكل مباشر في موثوقية الفولاذ المستخدم في العديد من الصناعات الحيوية، مثل صناعة السيارات، والنفط والغاز، وقطاع البناء، والمعتمدة بصورة أساسية على الهياكل والمنشآت الفولاذية. وقد تناولت العديد من الدراسات والأبحاث العلمية هذه الظاهرة ولكن فهم آلياتها ما يزال غير مكتمل بشكل كافٍ. لذلك، فإن معالجة هذه المشكلة تتطلب أولًا دراستها والعوامل المؤثرة في حدوث هشاشة الهيدروجين. تناولت هذه الدراسة استعراض الأدبيات والدراسات المتعلقة بهشاشة الهيدروجين في الفولاذ عالي المقاومة، وتأثيرها في الأنابيب الفولاذية المستخدمة في البيئات المائية. كما تركز على التطورات والأساليب الحديثة التي أدت لفهم العلاقة بين البنية المجهرية للفولاذ وخصائصه وأدائه والتركيز على العوامل المسببة لهشاشة الهيدروجين والمؤثرة فيها.

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وقد تم عرض هذه الورقة العلمية في جلسات المؤتمر الدولي للطاقة المتجددة والنفط والغاز وتغير المناخ "أيريقو" في الفترة 25-27 ابريل 2026م. طرابلس – ليبيا

الكلمات المفتاحية: هشاشة الهيدروجين، الفولاذ عالي المقاومة، خطوط أنابيب الصلب، AIDE، HELP، HPT، HEE

Introduction

The progressive depletion of fossil fuel reserves and the growing environmental concerns over greenhouse gas emissions have intensified the global search for alternative, cleaner energy sources. Hydrogen has become a cornerstone in the current drive for clean energy worldwide and offering the potential to decarbonize several sectors, especially when used as a blend with natural gas in existing infrastructure. Blending hydrogen with natural gas is increasingly viewed as a pragmatic and transitional strategy for reducing carbon emissions in both residential and commercial domains. The combustion of hydrogen yields only water, releasing no carbon dioxide, which makes hydrogen-natural gas blends particularly attractive for countries striving to meet aggressive emission reduction targets [1,2].

Hydrogen, the most abundant element in the universe, is a promising alternative energy carrier for a sustainable future [3, 4]. Its potential as a clean energy source, particularly in industrial applications such as fuel cells, power plants, and hydrogen-blended natural gas pipelines, is underscored by its growing importance in the global energy transition [5-8]. Designing pipelines specifically for pure hydrogen is costly and time-consuming, costing 30-50% more than using natural gas pipelines, suggesting that using existing natural gas transportation systems is a viable option [1, 9].

Combustion of hydrogen produces only water, with no carbon dioxide emissions, making a hydrogen-natural gas blend particularly attractive for countries striving to achieve ambitious emissions reduction targets [2]. However, hydrogen utilization presents significant challenges. One of the most important concerns associated with hydrogen utilization

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is hydrogen-induced environmental embrittlement (HEE), a phenomenon in which the mechanical properties of materials deteriorate when exposed to hydrogen-rich environments .The occurrence of (HEE) depends on the complex interaction of multiple factors. Among these, the type of hydrogenated environment plays a pivotal role, encompassing parameters such as pressure, temperature, hydrogen purity, form, and source. Another crucial determinant is the specific metal under study, which includes aspects ranging from its primary crystal structure to its microstructure, heterogeneity, substructure conditions, phase stability, strength level, surface conditions, and others [10].

A third vital factor is the stress domain, which considers factors such as the type of load (uniform or cyclic), the state of the applied stress, and the presence of residual stress. While the individual effects of these factors have been extensively studied over time, understanding their synergistic interaction remains a complex challenge [11]. Figure 1 provides a schematic representation of the dependence of these factors on the susceptibility of industrial equipment to hydrogen corrosion [12].

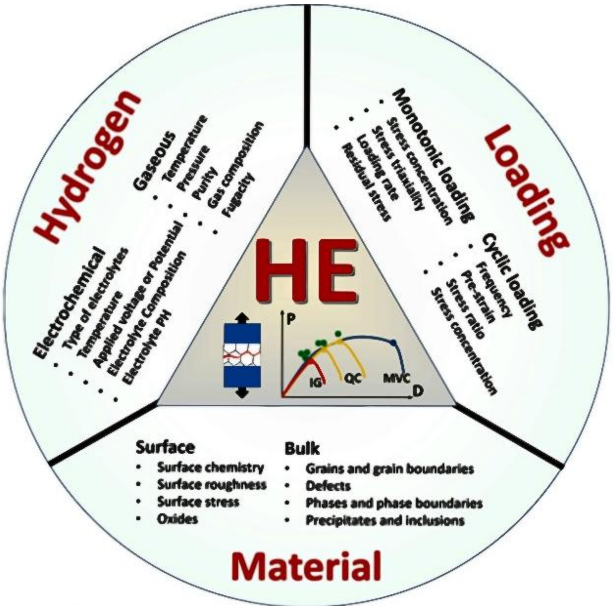

Figure.1. Schematic illustration of influencing factors of HE [12].

HE (Hydrogen Embrittlement) remains an open and active research area. The difficulty of HE study lies mainly in two aspects. First, measuring the effect of HE experimentally is extremely challenging, and precise mapping of HE distribution in materials has become possible only recently. Secondly, HE is a multidisciplinary subject that calls for expertise in several areas, e.g., electrochemistry, material science, and mechanics, to comprehend. This issue poses significant risks to the reliability and safety of materials, particularly in high-pressure and cyclic loading scenarios. This phenomenon can precipitate catastrophic failures under mechanical stress, undermining the structural integrity of pipeline infrastructure [1,13,14].

Given the significant risks posed to energy security and infrastructure safety, a robust and accurate understanding of the effects of hydrogen on pipeline steel is essential for the safe and efficient deployment of hydrogen and natural gas blends. This comprehensive review aims to synthesis the current state of knowledge on hydrogen embrittlement in pipeline steels, with a particular focus on natural gas-hydrogen blends. It critically examines the mechanisms of embrittlement, which to assess the viability of hydrogen blending in existing pipeline networks.

I. Hydrogen Embrittlement Mechanisms

Basic understanding of mechanisms of hydrogen embrittlement in pipeline steel relies on the hydrogen characteristics. Hydrogen's unique properties, such as its lightweight, rapid diffusion, and high activity, allow it to penetrate metal lattices, causing degradation via mechanisms such as microcrack propagation and embrittlement. Hydrogen, even at low concentrations (<1ppm), can weaken high-strength materials, leading to fracture formation, reduced ductility, and catastrophic failures [15]. These impacts are especially concerning in businesses where hydrogen is stored, transported, or used in severe environments, such as pipelines, fuel cells, and aerospace applications. As shown schematically in Fig.2, hydrogen atoms penetrate the surface of the pipeline steel through three main continuous processes [15,16]. reducing its ductility and load-bearing capacity, which can lead to cracking and catastrophic brittle failures even under stresses below the material' s yield strength [17,18].

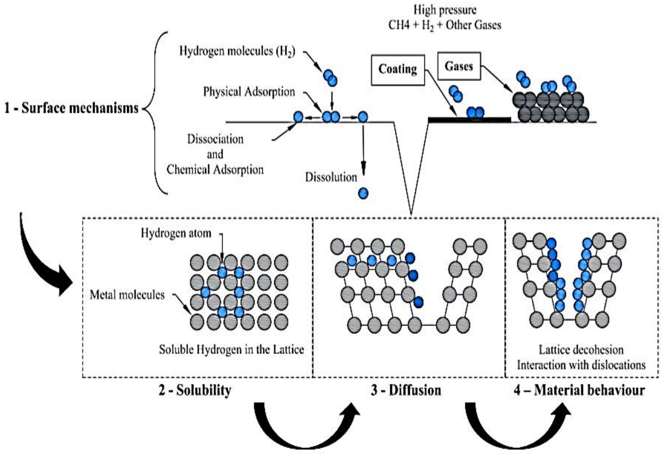

Figure.2 Schematic illustration of hydrogen embrittlement mechanism [19]

Hydrogen embrittlement is a complex, multifaceted phenomenon that manifests as a reduction in ductility, toughness, and fatigue resistance of metals exposed to hydrogen. The ingress of hydrogen atoms into the metal lattice can lead to localized or intergranular fracture, even when the metal is subjected to stresses much lower than the nominal strength of the material [13,14,20,21].The susceptibility of pipeline steels to HE depends on several factors, including steel composition, microstructure (grain boundaries, dislocation density, inclusions), hydrogen concentration, and exposure conditions. The precise mechanisms by which hydrogen induces embrittlement remain a subject of ongoing debate and investigation. Nonetheless, several dominant theories have been proposed, each shedding light on different facets of the phenomenon. The following sections will cover several HE mechanisms.

II. MECHANISTIC THEORIES

A Hydrogen-Enhanced Decohesion (HEDE)

The HEDE theory posits that hydrogen atoms, when segregated at locations of high triaxial stress (e.g., grain boundaries), weaken the atomic bonds within the metal lattice, precipitating intergranular or quasi-cleavage fracture [22]. Theoretical and computational studies demonstrate that hydrogen reduces the cohesive energy of grain boundaries, facilitating fracture initiation [23]. However, critical questions persist regarding the threshold hydrogen concentration required to trigger fracture and the ability of service conditions to achieve such levels.

B. Hydrogen pressure theory (HPT)

The Hydrogen Pressure Theory (HPT) suggests that steel degradation results from hydrogen accumulation in voids, increasing internal pressure and promoting void growth and crack propagation [22,23]. Dislocations act as diffusion pathways, accelerating hydrogen-assisted cracking (HAC) even at low hydrogen pressure [24-26]. Observations of stable crack growth in dry hydrogen and other gaseous environments indicate that pressure buildup is not always the primary cause. Theoretical predictions often overestimate hydrogen flow rates and underestimate its escape, leading to inaccuracies in pressure buildup estimations near voids [27].

a. Hydrogen-Enhanced Localized Plasticity (HELP)

The HELP mechanism suggests that hydrogen enhances dislocation mobility, increasing localized plasticity near crack tips and lowering the resistance to crack propagation [13,14, 28]. Experimental evidence of well-developed dislocation structures beneath fracture surfaces supports this theory. However, subsequent studies have also shown that, under certain conditions, Hydrogen can impede dislocation motion, indicating that the interplay between hydrogen and plasticity is nuanced and context-dependent.

b. Adsorption-Induced Dislocation Emission (AIDE) and Other Mechanisms

Additional mechanisms, such as AIDE, hydride formation, hydrogen-assisted micro-void coalescence, and hydrogen-enhanced strain induced vacancy formation, have been proposed to explain specific aspects of hydrogen-induced failure [2,20,21]. Notably, recent in-situ diffraction studies have revealed the formation of metastable hydrides in stainless steels, challenging the earlier view that hydride formation is negligible in such alloys and underscoring the importance of real-time measurement in understanding embrittlement processes [21].

III. EXPERIMENTAL FINDINGS

Degradation of Mechanical Properties

Hydrogen-induced degradation represents a critical challenge for steel used in pipeline applications. Hydrogen embrittlement (HE) has been shown to cause a pronounced loss of ductility, a reduction in fracture toughness, and an increase in fatigue crack growth rates (FCGR). Experimental investigations on high strength steel grades (X70 and X65) pipeline steels have demonstrated significant ductility reduction in hydrogen environments compared to helium or other inert conditions as shown in figure 3.

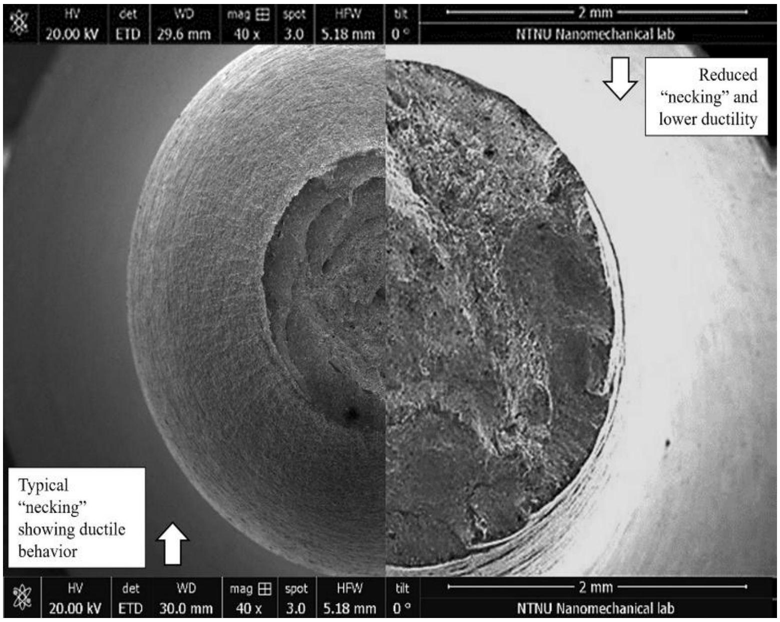

Figure. 3. Hydrogen-induced loss of ductility on a X65 pipeline steel.[31].

The severity of this reduction increases at slower strain rates and at hydrogen pressures around 5.5 MPa, which allow for longer hydrogen exposure times and enhanced embrittlement effects [29]. Similarly, fracture toughness is negatively influenced by hydrogen; for instance, a threshold concentration of approximately 1 ppm in X70 steel is sufficient to lower fracture toughness, with a near linear correlation between hydrogen concentration and resistance to crack propagation. The behavior of welds and heat-affected zones (HAZ) has been found to be inconsistent across studies: while some results indicate improved resistance in welds, others confirm greater susceptibility within these zones [30].

The studies on high strength steel grade (X70) welds compared with base metals provided mixed findings: in some cases, welds appeared less susceptible to hydrogen embrittlement due to hydrogen trapping within microstructures, while in others, welds were found to be more vulnerable than the base steel [32,33]. Fatigue testing on welded high strength steel grade (X60) revealed that hydrogen accelerated fatigue crack growth by factors of four in the base metal and eight in welds, leading to an overall reduction in pipeline lifetime by about 37–57% [34].

Another study evaluates the fatigue performance of high strength steel grade (X80) pipeline steel under different hydrogen concentrations. The results show that even small amounts of hydrogen drastically reduce fatigue life (up to 80% at 6% H), with crack propagation being more strongly affected than initiation. Fracture behavior shifts from ductile in air to mixed brittle ductile, with clear embrittlement features such as planar fracture regions becoming pronounced beyond 12% H [35].

In high strength steel grade (X80), fatigue crack growth rates doubled when hydrogen pressure increased from 0.2 to 8 MPa [36]. The effect of loading frequency was also significant: lower frequencies, in the range of 1 to 0.01 Hz, allowed more hydrogen diffusion at crack tips and caused more severe fatigue degradation [37]. Temperature played a key role as well, with the worst degradation occurring near ambient conditions (~273 K). At very low or high temperatures, the damaging effect was reduced due to either lower hydrogen diffusivity or faster desorption [38]. High-strength steels such as (X100 were observed to be more prone to embrittlement compared to lower-grade steels. For this reason, American

Society Mechanical Engineers (ASME) [B31.12] places restrictions on their use in hydrogen service [39]. On the mitigation side, gas blending and inhibitors demonstrated varying levels of effectiveness. Oxygen and carbon monoxide were strong inhibitors of hydrogen uptake, methane provided a modest reduction effect, and surface-active compounds such as lanthanum salts and iron oxides were found to form protective layers that limited hydrogen interaction with the steel surface [40].

V. HYDROGEN EMBRITTLEMENT RESISTANCE

Proposed Mechanisms to Improve the Resistance of Strength Steel to Hydrogen Embrittlement.

The latest technologies in hydrogen permeability prevention focus on incorporating diverse materials and techniques to mitigate the damaging effects of brittleness. These technologies include a variety of coatings. Hydrogen leakage into materials can be detrimental due to corrosion and brittleness. The design and performance of barrier coatings engineered to prevent hydrogen absorption, leakage, and penetration have seen significant advancements. Alternative coating concepts can offer greater resistance to hydrogen isotope permeability, and some recent studies have demonstrated their effectiveness, such as oxides, nitrides, carbon, and carbides [41]. Microstructure plays a role in hydrogen diffusion, with phases, grain boundaries and size, voids, dislocations, and impurities acting as hydrogen traps. Reducing the carbon, silicon, phosphorus, and sulfur content, as well as the chemical ratios of manganese in pipeline steel, are effective measures. Vacuum degassing during manufacturing also reduces hydrogen content, followed by low-temperature annealing after casting. Other factors include annealing processes, mechanical forming, alloying additives such as niobium and titanium, and environmental conditions such as temperature and humidity [42].

VI. CONCLUSION:

Hydrogen embrittlement in high-strength steel used in natural gas pipelines in aqueous environments poses a significant challenge to the structural integrity of this steel, as it is a major factor in its long-term deterioration. The presence of hydrogen leads to a decrease in the steel's mechanical properties through loss of ductility, reduced fracture resistance, and increased susceptibility to crack growth and progression into fractures that accelerate metal failure. The presence of these pipelines in an aqueous environment facilitates hydrogen diffusion and accelerates the deterioration process in hydrogen-carrying pipes. The study revealed that welded zones and heat-affected zones have varying susceptibility to this phenomenon due to differences in their microscopic properties and the distribution of residual stresses from the welding process .Furthermore, all these effects lead to an increased risk of containment within gas transmission lines, as these types of high-strength steel are more susceptible to this phenomenon. To ensure safety in the operating environment, current standards recommend avoiding their use and focusing in the future on the importance of the steel's microstructure and the possibility of including it in the specifications for selecting materials for hydrogen transmission pipelines [43]. It is also recommended to clarify the behavior of welds and thermal influence zones and to develop improved steel types and coatings.

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