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Calculation of the Damage Factor for the Hydrogen-Enhanced Fatigue in the RBI Framework

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Hydrogen has been largely indicated as a promising long-term solution for energy transport and storage, thanks to its near-zero environmental impact at the end-use site. On the other side, it can permeate and embrittle most metallic materials, thus resulting in sudden component failures in the hydrogen industry. Maintenance activities have a prominent role in accident prevention. The risk-based inspection (RBI) approach aims at prioritizing the inspection of high-risk components to minimize the overall risk of the plant. Nevertheless, RBI has never been adopted for equipment operating in a hydrogen environment. The determination of the risk is based on the damage factor, a parameter accounting for the material degradation likely to occur. Hydrogen-induced damages are mostly neglected or generalized by the existing RBI standards. This study proposes a methodology to determine the damage factor for hydrogen-enhanced fatigue crack growth, normally caused by pressure fluctuations in pipeline systems. The environmental severity is based on the operating conditions, while the material's susceptibility depends on its microstructure, chemical composition, and presence of welds. The working conditions are considered through the frequency and the stress ratio. This methodology could allow the application of the RBI methodology for hydrogen-related equipment. Hence, it will facilitate risk-informed managerial decisions, thus stimulating an increasingly widespread rollout of hydrogen as a clean and safe energy carrier.

Keywords: Risk-based inspection, Hydrogen damage, Fatigue crack growth, Material degradation, Loss of containment, Predictive maintenance, Maintenance planning.

1. Introduction

The rising demand for clean and sustainable energy imposes a paradigm change in several industrial sectors. In such context, hydrogen has been largely indicated as a promising vector to channel large amounts of energy from the production sites to the end-users. It can be produced by steam-reforming or by water electrolysis and used with near-zero pollutant emissions in fuel cell systems (Ustolin et al., 2022). Despite this, the market penetration of hydrogen technologies is braked by safety concerns from the industry stakeholders and the general public. In particular, the detrimental effect of hydrogen on metallic materials represents a critical issue. Although hydrogen-induced damages (HDs) have been largely investigated over the years, they are still responsible for many industrial failures and undesired hazardous releases in the environment (Campari et al., 2023). Most of these equipment breakdowns are preceded by premonitory signs that, if timely observed and correctly interpreted, could avoid the occurrence of undesired events.

Inspection activities have the potential to detect these failure precursors and allow the implementation of preventive measures. Effective inspection planning can keep the risk level below a predetermined threshold, while guaranteeing an acceptable availability of the facilities. The risk-based inspection methodology has been largely indicated as the most beneficial guideline for inspection planning in the chemical and petrochemical sectors. It is grounded on the assumption that risk is not equally distributed among the individual pieces of equipment, and a large percentage of the total risk is concentrated in a comparatively small number of components. RBI can be used to identify these critical items and prioritize their inspection, thus minimizing the costs and guaranteeing the plant's service under safe conditions. Nevertheless, the existing RBI framework does not consider the majority of HDs and applies to hydrogen technologies only with highly unrealistic assumptions (Campari et al., 2022).

Normal pressure fluctuations in pipeline systems may result in fatigue degradation, especially in the proximity of weldments and heat-affected zones (HAZs). If the material has a pre-existing microcrack, hydrogen highly enhances the fatigue crack growth rate (FCGR), thus compromising the component's integrity over time. This study aims at developing a qualitative methodology to evaluate the hydrogen-enhanced fatigue crack growth rate (HEFCGR) in pipelines. It could aid the application of the RBI methodology for equipment subjected to cyclic loading in H_2 environments and facilitate risk-informed decisions regarding their inspection and maintenance.

2. Hydrogen pipelines

Hydrogen transport through the natural gas pipeline network can influence the degradation over time of the construction materials. Pipeline steels evolved over the years to obtain an optimal combination of mechanical properties. The elastic limit increased while maintaining or even increasing the fracture toughness. On the other hand, the elongation at failure slightly decreased, along with the carbon content in order to increase the weldability. The American Petroleum Institute (API) categorizes the most common pipeline steel grades (Pluvinage, 2021). Until the 1960s, low-grade steels have been used for pipeline applications. In Europe, around 70% of the pipe network is manufactured in Grade B, X46, and X52 steels. Despite this, the use of higher-grade steels, such as X56, X60, X65, and X70, allows for an increase in the internal pressure, thus making gas transport more efficient. Despite this, the increase in pressure, especially in H_2 environments, leads to enhanced hydrogen-induced material degradation. Further improvements in manufacturing techniques and microalloying allowed the development of X100 and X120 steels, even if they are not yet being used. The distribution of steel grades in the European pipeline network for natural gas is depicted in Figure 1.

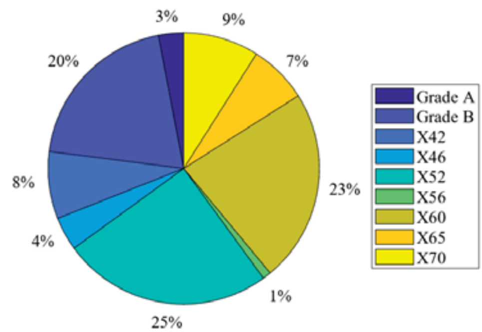

Fig. 1. Steel grades in the European pipeline network (adapted from Pluvinage (2021))

Depending on the production year and the manufacturing process, pipeline steel grades exhibits different compositions and various microstructures. Steels grades lower than X70 are characterized by a mixture of pearlite and ferrite arranged in longitudinal bands resulting from the rolling process. Higher-grade steels usually present mixtures of ferrite and bainite in more fine-grained microstructure, which allow better mechanical performances. In addition, the formation of martensitic-austenitic brittle islands is common in welds and heat-affected zones. These structures are the consequence of the thermo-mechanical controlled rolling inherent to the pipeline manufacturing process. According to API 5L, the pipeline steels grade classification relates to their Specified Minimum Yield Strength (SMYS). Yield and ultimate tensile strength ranges are summarized in Table 1 for grades up to X120 (API, 2018).

Table 1. Yield strength and ultimate tensile strength for pipeline steels (API, 2018)

Steel grade	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]
Grade A	210	335
Grade B	245	415
X42	290 - 495	415 - 655
X46	320 - 525	435 - 655
X52	360 - 530	460 - 760
X56	390 - 545	490 - 760
X60	415 - 565	520 - 760
X65	450 - 600	535 - 760
X70	485 - 635	570 - 760
X80	555 - 705	625 - 825
X90	625 - 775	695 - 915
X100	690 - 840	760 - 990
X120	830 - 1050	915 - 1145

The design operating conditions for hydrogen pipelines are indicated in the standard ASME B31.12 (ASME, 2019). Hydrogen pressure up to 207 bar is allowed for pipes made of X42 up to X60, while a complete fracture and fatigue performance quantification is required if the gas pressure exceeds this value. For higher strength steels, such as X70 and X80, the design pressure should be limited to 104 bar. The suitability of higher steel grades for hydrogen transport remains to be assessed.

2.1. *Hydrogen-enhanced fatigue*

Even if piping systems ideally should not be subject to direct mechanical fatigue loading, failure of pipe supports, vibrations of unbalanced dynamic machinery, chattering of pressure relief devices, pressure fluctuation during normal operations, and pressure cycles under upset conditions could render them susceptible to fatigue failures (Campari et al., 2023). In addition, it is well known that FCGR is accelerated when steels are exposed to hydrogenated environments (Brocks Hagen and Alvaro, 2021). Pipelines are normally designed through defect-tolerant principles and unavoidable minor imperfections often represent crack initiation sites, making these systems highly susceptible to HEFCGR. The mechanism of crack propagation in hydrogen is very complex and can be affected by various factors, such as the material's microstructure, the presence of stress concentrations, the environmental conditions, and the characteristics of the cyclic load (Lokhande and Vishwakarma, 2022).

Pipelines are operated under variable-amplitude cyclic loading. Three types of pressure fluctuations are likely to occur during normal operations: underload, mean load, and overload. Underloads are verified downstream of compressors and are characterized by large fluctuations with low stress intensity ratios ($R = \frac{K_{min}}{K_{max}}$) and minor fluctuations with high R-ratios. The average load is close to the design limit of the pipe. Mean loads are observed further down from compression stations. In this case, the average load is lower, but pressure frequently rises above this value. Overloads are characterized by pressure peaks above the mean value and are frequently observed in the proximity of a suction site. Underload-type fluctuations are the harshest in terms of FCGR since they induce the highest maximum stress intensity factor (K_{max}) and the largest stress intensity range (ΔK) (Zhao et al., 2016). The major pressure cycles result from the daily fluctuations of the fuel demand, which is maximum during daytime and decreases over night. Pipelines are designed to withstand these fluctuations due to the cycling operating pressure related to the periodic demand. In other words, the pipeline network has the double function of transport and storage system, often referred to as "line packing". These daily pressure fluctuations are very low in frequency (approximately 10^{-5} Hz), relatively high in amplitude (ΔK ranging from 15 to 20 $MPa\ \sqrt{m}$), and R values around 0.25 (Zhao et al., 2016). On the other hand, minor pressure fluctuations from compression stations have frequency ranging from 10^2 to 10^3 Hz, low amplitude, and R values above 0.5.

Being hydrogen degradation a time-dependent phenomenon, the acceleration induced by hydrogen on the FCGR is inversely proportional to the frequency: in general, a higher acceleration in FCGR is measured for a given ΔK value as frequency is decreased. In addition, the hydrogen-enhanced crack propagation is more pronounced for high ΔK. The R-ratio influences the hydrogen diffusion and its effect on the FCGR. The fatigue propagation in hydrogen remains almost unchanged for R values between 0.1 and 0.4 but increases sharply at R above 0.4. In fact, crack closure effects aside, the higher the R value, the higher the mean stress will be and, consequently, the higher the hydrogen diffusion rate (Nanninga et al., 2010). Considering the materials' susceptibility, it has been observed that steel grades with an acicular ferritic structure are more sensitive to HD than grades with ferritic-pearlitic microstructures because of the higher hydrogen diffusivity (Laureys et al., 2022). Despite this, pipelines with the same steel grade can show different microstructures depending on the manufacturing technique adopted. For this reason, a vintage X52 can significantly differ from a modern X52 in terms of fatigue performance (Slifka et al., 2018). In addition, the variations in microstructure between base metal, welds, and HAZs often result in different fatigue behavior. Welded areas are normally more susceptible to HEFCGR due to the local formation of martensite and the presence of minor defects and residual stresses (Drexler et al., 2019).

Figure 2 shows the typical FCGR curve for two pipeline steels obtained when tested both in pressurized hydrogen gas and in air.

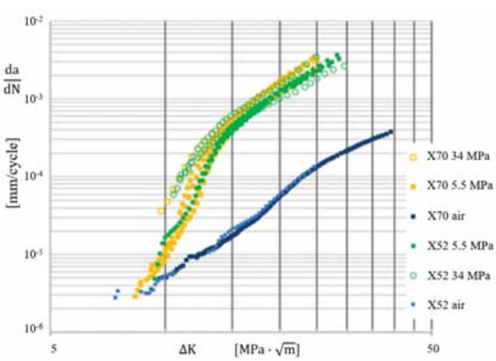

Fig. 2. FCGR in X52 and X70 steels tested in hydrogen at 5.5 MPa and 34 MPa, compared to tests in air (Amaro et al., 2018)

3. Risk-based inspection methodology

Inspections are a vital part of predictive maintenance. While inspection activities do not inherently mitigate the probability of failure, they have the potential to reduce the uncertainty in determining the risk. If correctly planned and performed, inspections can monitor equipment degradation status allowing for a more precise prediction of the failure date, and making preemptive intervention possible. Risk-based inspection is a decision-making methodology for optimizing inspection plans. It assumes that the risk of failure can be assessed and maintained below an acceptable level through inspections and repairs. Since most of the total risk in an industrial facility is determined by a few pieces of equipment for which the probability and/or the consequence of failure is more significant, those are given priority for inspection. RBI strategy allows the selection of cost-effective and rational inspection and maintenance techniques.

The calculation of risk is based on the definition by Kaplan and Garrick (1981) and is given by the product of the probability of failure and its consequence:

$$R_f(t, I_E) = P_f(t, I_E) \cdot C_f \tag{1}$$

where P_f and C_f represent the probability and consequence of failure, respectively, t is the time, and I_E is the effectiveness of previous inspections. While the consequences of failure are determined through well-established consequence analysis techniques and expressed in financial terms or as an impact area, the probability of failure can be determined through the product of three factors:

$$P_f(t, I_E) = gff \cdot D_f(t, I_E) \cdot F_{MS} \tag{2}$$

where gff represents the generic failure frequency, D_f the damage factor, and F_{MS} the management system factor. The generic failure frequency is defined as the number of failures per year of a certain type of component operating in a benign environment; it is provided in the recommended practice API 581 (2019) and based on historical data. The damage factor adjusts the gff, considering the real operating conditions of the component and its susceptibility to a certain damage, and it depends on service time, number and effectiveness of previous inspections. The management system factor accounts for the probability that damages will be detected before the failure. Since F_{MS} is applied equally to all the plant's components, it does not change the risk-based ranking. The first step of the RBI methodology is the collection and validation of historical data and technical details of the plant. Secondly, the active damage types must be identified and the P_f must be calculated. All the failure scenarios likely to occur should be considered, together with their consequences. Thus, it is possible to calculate the risk level associated with each component and rank them accordingly. The inspection plan is developed, prioritizing the high-risk items. Mitigation activities, i.e., maintenance, repair, or components' replacement, are carried out whenever required to keep the overall risk below a predetermined threshold. Finally, the process is reassessed based on the results of previous inspections (API, 2016).

4. Calculation of the damage factor

According to API RP 581 (2019), the base damage factor for mechanical fatigue in pipes and pipelines can be calculated through Eq. 3.

$$D_{fB}^{fat} = max\left[D_{fB}^{pf},\ \left(D_{fB}^{as} \cdot F_{AS}\right),\ D_{fB}^{cl}\right] \quad (3)$$

where D_{fB}^{pf} represents the base damage factor for previous failures, D_{fB}^{as} accounts for visible or audible shaking, and D_{fB}^{cl} is the base damage factor for the type of cyclic solicitations connected to the pipe (i.e., a reciprocating machinery, a chattering pressure relief device, or a valve with high pressure drop). F_{AS} is an adjustment factor related to the magnitude of the vibrations with respect to the component's endurance limit. Then, the damage factor for mechanical fatigue can be obtained by applying five adjustment factors to the D_{fB}^{fat} calculated through Eq. 3.

$$D_{f}^{fat} = D_{fB}^{fat} \cdot F_{CA} \cdot F_{PC} \cdot F_{CP} \cdot F_{JB} \cdot F_{BD} \quad (4)$$

where F_{CA} is the adjustment factor for corrective actions, F_{PC} considers the pipe complexity (i.e., the number of fittings), F_{CP} accounts for the conditions of the pipe (i.e., improper support or broken gussets), F_{JB} is the adjustment factor for the joint/branch type, and F_{BD} considers the branch diameter.

If the component operates in hydrogenated environments, as in the case of pipes for H_2 transport and distribution, the hydrogen-enhanced fatigue crack growth rate should be taken into account through additional adjustment factors. This approach is based on the assumption that hydrogen only influences the FCGR and does not affect the threshold for crack propagation (ΔK_{th}). The damage factor for hydrogen-enhanced fatigue (HEF) can be calculated through Eq. 5.

$$D_{f}^{HEF} = D_{f}^{fat} \cdot F_{H_2}^{p} \cdot F_{H_2}^{mat} \cdot F_{H_2}^{pur} \quad (5)$$

where $F_{H_2}^{p}$ represents the adjustment factor for the hydrogen pressure, $F_{H_2}^{mat}$ accounts for the material used and the part of the pipe considered, and $F_{H_2}^{pur}$ is the factor for the hydrogen purity and the presence of inhibitors. Figure 3 shows the flow diagram for the calculation of the D_{f}^{HEF}.

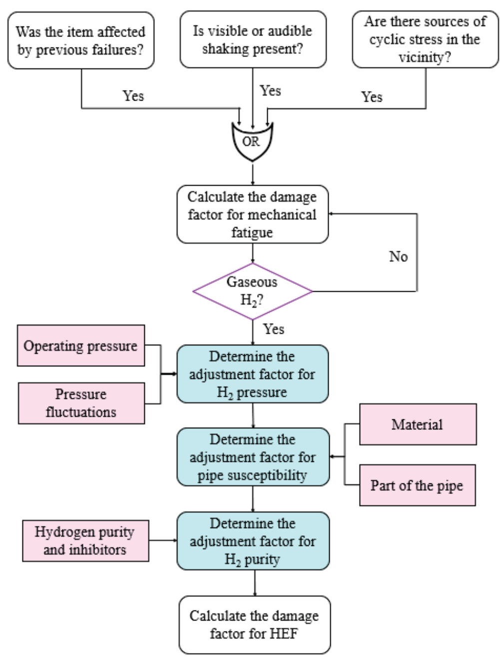

Fig. 3. Flow diagram for the determination of the damage factor for HEF

The adjustment factor $F^{p}_{H_2}$ takes into account the operating pressure of the pipeline (up to 207 bar, according to the standard ASME B31.12) and its daily pressure fluctuations. On the one hand, the pressure is the driving force for hydrogen uptake within the metal, on the other the pressure fluctuations are responsible for the cyclic load which triggers the fatigue damage. A qualitative indication for $F^{p}_{H_2}$ can be found in Table 2. $F^{mat}_{H_2}$ depends on the construction material and the position of the stretch of pipe (downstream of a compressor, along the pipeline, or upstream of a suction site). The most susceptible materials are indicated, distinguishing between base metal (BM), welded area (WA), and HAZ. The susceptibility of the pipeline is qualitatively determined through Table 3. Finally, $F^{pur}_{H_2}$ accounts for the hydrogen purity and the presence of inhibitors. Only concentrations that are proven to be effective against HEFCGR and do not cause other issues (e.g., corrosion or formation of ignitable mixtures) are included in Table 4.

5. Discussion

The existing RBI codes and standards do not consider the effect of the operating environment for the calculation of the damage factor for mechanical fatigue. In particular, pipes and pipelines exposed to compressed gaseous hydrogen are prone to HEFCGR, which can drastically reduce their operating life, eventually leading to catastrophic failures. Natural gas pipelines are well-known systems, and their failure frequency is provided depending on their characteristics and size. Nevertheless, reliability data for hydrogen transport pipelines are not available, given the limited operational experience with this technology. In this perspective, the qualitative methodology proposed modifies the fatigue damage factor through three corrective coefficients that take into account the accelerated FCGR due to hydrogenated environments.

As already mentioned, the design pressure and amplitude of daily pressure fluctuations are deemed the most relevant operating parameters. The frequency at which the cyclic fluctuation are imposed to the pipe significantly affects the FCGR response of the steel, but it depends on the daily variations of hydrogen demand and is roughly the same for all the pipelines. In addition, the pipeline susceptibility to fatigue cracking is a function of the construction material and the stretch of pipe considered. The code ASME B31.12 indicates the Specified Minimum Yield Strength as the main factor for HE susceptibility in pipeline systems, thus penalizing high-strength steels. This principle is generally valid for monotonic loading conditions but, in the case of cyclic loads, the correlation between material strength and magnitude of HEFCGR is not the same. HEFCGR has been observed in both low-strength (e.g., X42 and X52) and high-strength steels (San Marchi and Somerday, 2012). Grain size and microstructure are the most influencing factors for material susceptibility to hydrogen-enhanced fatigue. In general, finer grains make the steel less susceptible to HEFCGR, and ferritic microstructures show higher hydrogen diffusion than bainitic and pearlitic ones (Park et al., 2008). In addition, HAZs and welds are considered more prone to FCGR than base metal because of residual stresses, less controllable microstructures, and geometrical imperfections that could act as fatigue crack initiation sites. Finally, the purity also plays a role. When hydrogen is blended with natural gas, its detrimental effect on the pipeline steel fatigue performance may be mitigated as a results of the presence of impurities which act as hydrogen uptake inhibitors. The inspection effectiveness does not affect the value of D_f for mechanical fatigue, according to API 581. Nevertheless, several inspection techniques capable of detecting fatigue cracks are indicated in Table 5. All these methods are suitable for in-service inspections and are non-destructive tests.

The main limitation of this study is represented by its qualitative nature. A limited number of experiments have been conducted to test the fatigue performance of high-strength pipeline steels and to compare them with low-grade steels, even if more research is now focused in that direction. In addition, there is still a dearth of studies concerning the response of pipeline steels to cyclic loads with variable amplitude and low frequency, which

Table 2. Environmental severity for hydrogen-enhanced fatigue

		Daily pressure fluctuations [bar]			
		$\Delta p \leqslant 5$	$5 < \Delta p \leqslant 10$	$10 < \Delta p \leqslant 30$	$\Delta p \geqslant 30$
Pressure [bar]	$p \leqslant 20$	Moderate	High	-	-
	$20 < p \leqslant 60$	High	High	Severe	-
	$60 < p \leqslant 120$	High	Severe	Severe	Extreme
	$120 < p \leqslant 207$	High	Severe	Extreme	Extreme

Table 3. Pipeline susceptibility to fatigue cracking

	Part of the pipe		
	Downstream of compressor	Along the pipe	Upstream of suction site
Gr. A - Gr. B - X42 - X46 WA/HAZ	Extreme	High	Severe
Gr. A - Gr. B - X42 - X46 BM	Severe	Moderate	High
X52 - X56 - X60 - X65 - X70 WA/HAZ	Severe	High	High
X52 - X56 - X60 - X65 - X70 BM	High	Moderate	High

Table 4. Gaseous inhibitors for HEFCGR (San Marchi and Somerday, 2012)

Inhibitor	Concentration [%]	Effect
CO	1-2	High inhibition
O_2	0.01	High inhibition
O_2	0.1	Complete inhibition
SO_2	2	High inhibition

Table 5. Methods for detecting fatigue cracks and their sensitivity (Shanmugham and Liaw, 1996)

Method	Sensitivity [mm]	Application
Electric potential	0.25	In-service inspection
Liquid penetrant	0.025 - 0.25	In-service inspection
Magnetic properties	0.076	In-service inspection
Acoustic emission	0.1	In-field testing
Ultrasonic	0.050	In-field testing
Eddy current	0.1	In-field testing
Infrared	n.g.	In-field testing
Gamma radiography	2% thickness	In-field testing

better simulate the actual operating conditions of the pipeline network. Machine learning predictions based on experimental data and fatigue crack growth simulations can facilitate and complement this procedure. After that, this modified RBI approach should be applied to a real case study and compared with well-established methodologies for inspection and maintenance planning (e.g., time-based or condition-based maintenance) (Campari et al., 2023). The RBI approach has the potential to reduce the downtime and costs associated with inspections of hydrogen pipelines while respecting the safety and reliability requirements.

6. Conclusions

This study presents a qualitative methodology to calculate the damage factor for hydrogen-enhanced fatigue. It has been demonstrated that material FCGR can accelerate up to three orders of magnitude in H_2 when compared with a reference environment. Hence, the most important influencing parameters and their mutual influence have been evaluated. From the side of the environmental characteristics, operating pressure, hydrogen purity, and presence of inhibitors, have been indicated as primary factors for HEFCGR.

The mechanical loading conditions and material strength and microstructure constitute the other fundamental factors. The susceptibility of different steels has been investigated, highlighting how the existing codes for hydrogen pipelines are overconservative for high-strength steels. In addition, the stretches of pipe downstream of compression stations have been indicated as the most susceptible to fatigue failures due to the underload-type pressure fluctuations. Finally, a selection of inspection techniques capable of detecting fatigue cracks has been provided. This methodology can facilitate inspection planning and preventive maintenance of hydrogen pipelines. Nevertheless, the proposed approach can only provide qualitative indications and should be validated through experimental data, and subsequently upgraded into a quantitative methodology. Additional knowledge of high-strength steels is also required in view of their future application in the emerging hydrogen industry.

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