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Factors affecting the integrity of pipelines transporting hydrogen containing media

Judit Kovács[1*,] and *János* Lukács[1]

[1] University of Miskolc, Institute of Materials Science and Technology, 3515 Miskolc-Egyetemváros, Hungary

Abstract. Pipeline transport of hydrogen is one of the challenges of our time, whether it is hydrogen blended into natural gas or pure hydrogen. Given the economic and environmental interest in using an existing natural gas transmission system for this purpose, it is worthwhile to take into account the factors affecting the integrity, through their investigation possibilities. The typical damage mode, the hydrogen embrittlement, can be investigated with the help of the following methods: standard tensile test; Slow Strain Rate Test (SSRT); fracture toughness tests; High Cycle Fatigue (HCF) tests; Fatigue Crack Growth (FCG) tests; full-scale pipeline section tests; microstructural analyses. For each method, characteristics can be associated expressing the resistance to damage and give possible way for the ranking of the materials and their welded joints. The applicability of the characteristics will be demonstrated for API 5L grade steels of different strength categories by processing a statistically meaningful amount of data.

1 Introduction

Pipelines provide the most efficient way to transport large volumes of fuel/natural gas. Pipelines would also be the most efficient way to transport large quantities of hydrogen (as a fuel or energy carrier). For the construction of such pipelines, the ASME B31.12 standard [1] can be used. Since the design tables for pipelines are based on tensile test data, other information e.g. fatigue crack propagation data and fatigue damage models for pipeline steels should be added to the standard. Existing pipelines could be recycled for hydrogen transport or newer, more suitable alloys could be used to design new pipelines. To achieve this, comprehensive research is needed for both old and new pipeline steels [2-7].

In the case of pipelines, it is also important to examine the effect of girth welds since the construction defects and material discontinuities occur in a much higher ratio in welds than in the other parts of the pipelines (Fig. 1.) [8].

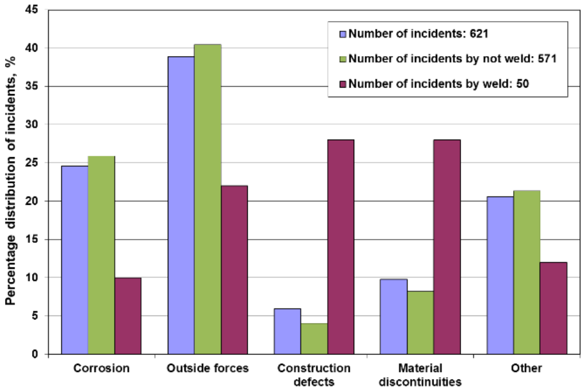

Fig. 1. Pipeline incident distributions by cause.

The Hungarian failure statistics demonstrate a more negative picture than the international data. The ratio of the weld defects in Hungarian hydrocarbon transporting pipelines is higher than the international practice and the weld defects typically occur in girth welds.

The aim of the present research work is to summarise the test methods for pipelines considered important for the determination of typical failure mode (which is Hydrogen Embrittlement) related to hydrogen.

2 Damages caused by hydrogen

A possible classification of the damage caused by hydrogen in metals and their alloys is shown in Table 1., with the abbreviations used in practice. The different kind of damages can be classified into several groups, and hydrogen embrittlement can be further specified.

Table 1. Damages caused by hydrogen in metals and their alloys [9, 10].

Abbreviation	Damage
HD	Hydrogen Damage
HB	Hydrogen Blistering
-	Shatter cracks, flakes, fisheyes
HTHA	High-Temperature Hydrogen Attack
MHF	Metal Hydride Formation
DFP	Degradation in Flow Properties
HE	Hydrogen Embrittlement
HE/HEE	Hydrogen Environment Embrittlement
HE/IHE	Internal Hydrogen Embrittlement
HE/HRE	Hydrogen Reaction Embrittlement

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[*] Corresponding author: judit.kovacs@uni-miskolc.hu

Considering that typically the base material of natural gas pipelines is carbon steel, and the operating temperature range is not very low or very high, the various types of hydrogen embrittlement are the primary concern.

The interaction between hydrogen and metals can result in the formation of solid solutions of hydrogen in metals, solid compounds as hydride, and gaseous compounds with other elements in the metal. Hydrogen embrittlement through these interactions can be classified into three categories: Hydrogen Environmental Embrittlement, Internal Hydrogen Embrittlement, and Hydrogen Reaction Embrittlement. The different factors affecting these three types of HE susceptibility are shown in Fig. 2. [11].

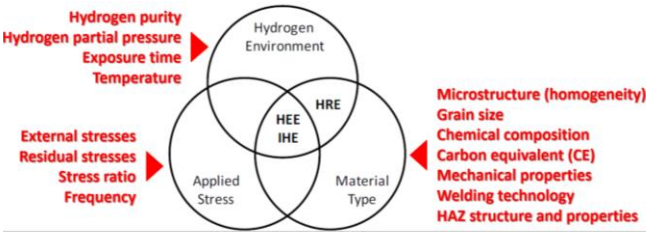

Fig. 2. Classification of HEE, IHE and HRE based on hydrogen environment, applied stress, and material type [11].

In case of HEE the materials are being exposed to a high-pressure gaseous hydrogen environment, while in case of IHE the source of hydrogen is not from a high-pressure gaseous system, but the hydrogen is from an electrochemical process (e.g. corrosion, cathodic charging); or the hydrogen come from moisture and enter the metals during welding, casting, and solidification processes. HEE and IHE require an external applied stress for the HE effects to occur. In case of HRE irreversible hydrogen damage happen due to a chemical reaction with hydrogen. This damage can occur without an external applied stress [11].

3 HE investigation possibilities

Pipes intended for the transportation of hydrogen should be comprehensively inspected to ensure safe operation. In order to obtain a sufficiently comprehensive evaluation of the resistance to hydrogen embrittlement, the following tests should be carried out:

- Slow Strain Rate Test (SSRT)
- Fracture toughness tests
- High Cycle Fatigue (HCF) tests
- Fatigue Crack Growth (FCG) tests
- Full-scale pipeline section tests
- Microstructural analyses

The relevant factors, indexes and curves that these investigations could provide are summarised in Table 2.

Table 2. HE investigation possibilities.

Investigation	**Relevant factors, indexes, curves**
SSRT	NTS ratio, RA ratio, EL ratio, EI
Fracture toughness tests	HEI, local fracture work (W_f)
HCF tests	Wöhler curves (S – N, L – N)
FCG tests	kinetic diagrams of fatigue crack growth, ERF
Full-scale pipeline section tests	burst pressure ratio, safety factor ratio
Microstructural analyses	fracture surface, grain size, microstructure

3.1 SSRT

With the help of SSRT the following factors can be calculated [11, 12]:

- Notched Tensile Strength ratio (NTS ration):

$$NTS\ ratio = \frac{NTS_{hydrogen}}{NTS_{air/helium}} \tag{1}$$

- Reduction of Area ratio (RA ratio):

$$RA\ ratio = \frac{RA_{hydrogen}}{RA_{air/helium}} \tag{2}$$

- Plastic Elongation ratio (EL ratio):

$$EL\ ratio = \frac{EL_{hydrogen}}{EL_{air/helium}} \tag{3}$$

- Embrittlement index (EI):

$$EI = \frac{RA_{reference\ environment} - RA_{H_2}}{RA_{reference\ environment}} \tag{4}$$

Research on hydrogen embrittlement has led to several different suggestions about the classification of the susceptibility of HE [13, 14]. A simplified suggestion for the classification (based on [13, 14]) is shown in Table 3. [11].

Table 3. Material screening for HE based on HEE index from NTS ratio [11].

HE category	**HEE index based on NTS ratio**	**Material screening notes***
Negligible	1.0-0.97	Materials can be used in the specified H pressure and temperature range with fracture mechanics and crack growth analysis in H.
Small	0.96-0.90	
High	0.89-0.70	Cautiously use only for limited applications with detailed fracture mechanics and crack growth analysis in H.
Severe	0.69-0.50	Not recommended for usage at specific pressure and temperature where the HEE index is measured.
Extreme	0.49-0.00	

* Based on application at specific H pressure and temperature, where HEE index is measured. In all categories, additional testing and fracture analysis must be performed beyond the material screening phase.

For example, the API 5L X52 material grade in [15] is in the high HE risk category.

Another approach based on EI is shown in Table 4.

Table 4. Material screening for HE based on EI [12].

HE susceptibility	**Application**	**EI**	**API 5L grades**
Negligible	Useable in pressurized H environments.	0.00-0.03	-
Small	Useable in H environments under controlled T and p.	0.04-0.10	X60, X65, X70
High	Usable for limited H applications with fracture and FCG analysis.	0.11-0.30	X42, X52
Severe	Not recommended for H applications.	0.31-0.50	X100
Extreme	Not usable for H applications at any T and p.	0.51-1.00	-

In the table the X52 material grade is classified with high HE susceptibility, but it can be classified as sever or extreme for older pipes e. g. [15].

3.2 Fracture toughness tests

The concentration of hydrogen in metal defines its local fracture resistance. The determination scheme of local fracture work can be seen in Fig. 3.

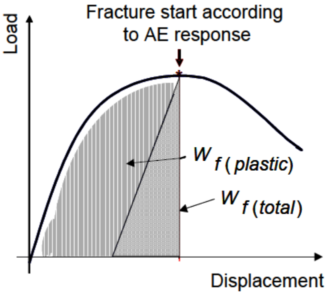

Fig. 3. The determination scheme of local fracture work [16].

With the help of fracture toughness test besides the local fracture work the Hydrogen Embrittlement Index (HEI) can be calculated as follows [17]:

- Hydrogen Embrittlement Index:

$$HEI = \frac{K_{Imat(H_2)}}{K_{Imat(air)}} \tag{5}$$

$$HEI = \frac{K_{JH}}{K_{JIC}} \tag{6}$$

3.3 HCF tests

For structures exposed to hydrogen, it is also important to know how hydrogen changes the S-N curve. Fig. 4. demonstrates the effect of hydrogen compared to air in case of S-N curve.

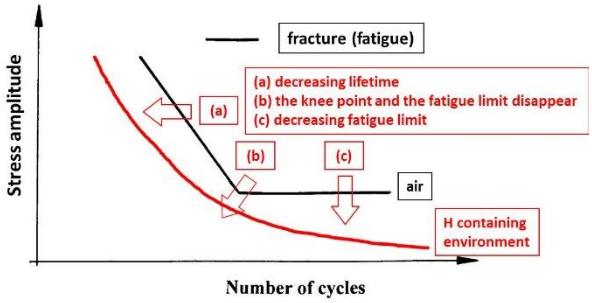

Fig. 4. Characteristics of S-N curves in air and in H containing environment [18].

The figure clearly shows that the lifetime and the fatigue limit decrease and the knee point disappears between the two stages.

3.4 FCG tests

A schematic diagram about the effect of dry gaseous hydrogen on fatigue crack growth in lower strength steels can be seen in Fig. 5.

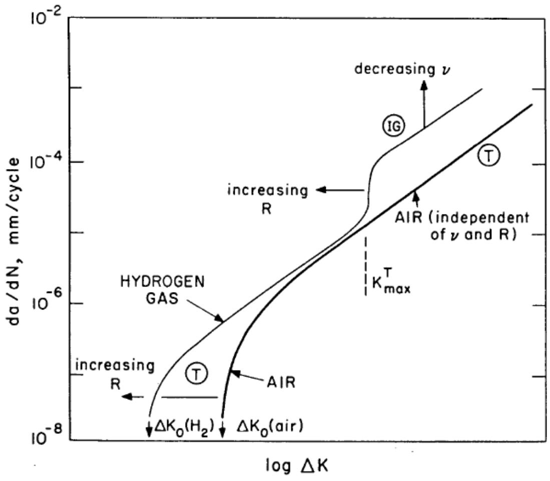

Fig. 5. Schematic diagram about the effect of dry gaseous hydrogen on fatigue crack growth in lower strength steels [19].

In the figure, the abbreviations are the followings:

- R : load ratio
- v : loading frequency
- T : predominantly transgranular fracture
- IG : predominantly intergranular fracture

Besides the kinetic diagrams of fatigue crack growth, the Environmental Resistance Factor (ERF) can be calculated [17]:

- Environmental Resistance Factor:

$$ERF = \frac{FCGR\ H_2}{FCGR\ air} \tag{7}$$

3.5 Full-scale pipeline section tests

Full-scale pipeline tests involve stretching and bending of a pipeline section until failure. The fundamental metric is strain capacity, which refers to how much longitudinal strain can the specimen withstand before failing, which is commonly referred to as maximum load. The tested pipeline section can also have girth welds. Artificial flaws are common in girth weld, thus the investigation of the effects of it can be also beneficial. When the failure occurs in the girth weld, the failure scenario frequently involves ductile ripping from the defect till the remaining ligament fails. An example to the damaged area of the pipeline section after the fatigue and burst tests can be seen in Fig. 6. [20].

Fig. 6. The damaged area of the pipeline section after the fatigue and burst tests.

With the use of full-scale pipeline section test, the followings can be determined:

- Burst pressure ratio (BPR):

$$BPR = \frac{BP_{H_2\ exposured\ pipeline}}{BP_{H_2\ not\ exposured\ pipeline}} \tag{8}$$

- Safety factor ratio (SFR):

$$SFR = \frac{SF_{H_2\ exposured\ pipeline}}{SF_{H_2\ not\ exposured\ pipeline}} \tag{9}$$

- Definition of the Safety Factor (SF):

$$SF = \frac{CP}{MAOP} \tag{10}$$

Where:

- CP: Characteristic Pressure = Burst Pressure (BP)
- MAOP: Maximum Allowable Operating Pressure Pressure = pipeline operational characteristics

3.6 Microstructural analyses

It is also important to analyse the microstructure in order to understand the changes in the material due to the presence of hydrogen. Microstructural analyses can be used to examine the fracture surface and determine, among other things, the grain size, and the microstructure.

4 Conclusions

Based on the present research work the following conclusions can be drawn:

- Making existing pipelines suitable for transporting hydrogen blended in natural gas or pure hydrogen is an environmental and economic necessity.
- The systematic preparation for the embrittlement of pipeline materials and their welded joints due to hydrogen is essential, with special emphasis of girth welds.
- For pipelines, from among of the forms of Hydrogen Embrittlement (HE), the Hydrogen Environmental Embrittlement (HEE) and the Internal Hydrogen Embrittlement (IHE) are probable.
- Hydrogen Embrittlement (HE) can be characterised on the basis of static and cyclic investigations; from the results of the different tests, HE can be described by different characteristics:
    - deformation parameters are more representative of changes than strength parameters,
    - due to the nature of the possible damages, fracture mechanical parameters are specifically suited to demonstrate the differences caused by HE.
- The behaviour of girth welds to Hydrogen Embrittlement (HE) can be derived from the base materials; different sensitivity to HE of the same base materials from different manufacturing periods is probable:
    - it is not enough to simply identify the base material and the filler metal, knowledge of the qualitative details (e.g. chemical composition) is also required,
    - girth welds can be considered as a higher risk site than base materials,
    - the degree of risk is further increased for girth welds made by pipes of different material types.

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