Meeting the Challenge - EUROPIPE Prepares for Hydrogen Pipelines

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Abstract

European natural gas pipeline operators are faced with future needs to transport hydrogen in their pipeline grids. To use renewable energy more efficient, it can be converted to hydrogen. From the past it is known for natural gas that pipelines are the safest and most economic measures to transport gas to the end users. As pressurized hydrogen might differently interact with carbon steel than natural gas, questions about suitability of carbon steel pipe came up. Near future scenarios set the industry's focus more on smaller diameters for pure hydrogen pipelines, whilst large diameter pipe is more dedicated to the application for hydrogen blends. As hydrogen quantities are expected to increase, also large diameter pipes might be used later for transporting pure hydrogen and the industry is going to be prepared for this situation.

For this reason, EUROPIPE has set up a program to evaluate the material behavior in pure hydrogen atmospheres and to support operators and designers with the results for their approach to safe pipeline operation. The program comprises investigations in different steels with different grades, chemistries, und microstructures. The focus is set on steels in the strength class between L450 to L485, as the hydrogen performance of those steels is generally considered to be more critical then lower grades.

As ASME B31.12 sets standards for worldwide hydrogen pipeline design and material property requirements, the program also focuses on testing according to this standard to evaluate the toughness level and the crack propagation behavior of carbon steels. This paper discusses the available results of this program and gives an overview about the influence of pressurized hydrogen on critical stress intensity and crack propagation under cyclic loading. The paper discusses also the reliability and significance of the available testing methods.

1. Introduction

The reduction of greenhouse gas results in the search for carbon neutral energy sources. Hydrogen might take over a fundamental role as energy transmitter, when produced by electrolysis from renewable energy or processed from natural gas with CCS technology. Hydrogen consumers from the chemical industry or the steel industry can use this gas for their processes and the public domain may use it for mobility and heating.

Transporting hydrogen to the consumer is an important issue to put a focus on. Depending on the required quantity to be transported, pipelines have proven in their application for natural gas that they are the safest and most economical means for transporting large quantities of gas. It is self-evident to transfer this also to transporting hydrogen, but the question rises, whether also the construction of hydrogen pipelines can use the same technical design for hydrogen than for natural gas.

In the past, many papers published that hydrogen can have a detrimental effect on carbon steel [1]. The operation of such pipelines was considered safe when using a steel grade at the lower end, as e.g. L360, with low SMYS usage [2]. In the past decades, hydrogen pipelines were designed in accordance with these principles and operator's experience is based on such pipelines. Modern natural gas pipelines use steel grades up to L555 and allows higher stressing of the pipe wall. The use of such design needs a detailed knowledge about the material's performance in hydrogen. Especially the toughness properties are of interest.

As of now, diameters up to 300 mm are selected to transport pure hydrogen in pilot pipeline projects to demonstrate the suitability of vintage and recently installed pipes. Larger diameter pipelines, in the diameter range of EUROPIPE's production, are more in the focus of blending hydrogen to natural gas. The study NATURALHY from 2009 stated that blends up to 20 % hydrogen does not have a significant de-rating effect on carbon steel [3]. However, material behavior in hydrogen depends more on the resulting hydrogen partial pressure than on the hydrogen percentage in the gas. This is different to the gas delivered to the consumers, where combustion properties are more linked to hydrogen percentage in the gas. Nevertheless, all of these considerations need the information about material's performance in hydrogen, which makes testing necessary, as only limited data for hydrogen performance of the current pipeline material in use are available.

Since decades, the pipeline industry copes with hydrogen absorption from wet natural gas contaminated with hydrogen sulfide in sour service or from cathodic overprotection. We could show that exposing carbon steel to pressurized hydrogen results in magnitudes lower atomic hydrogen contents in the steel than other hydrogen sources (Table 1). This leads to the conclusion that sour service features like hydrogen induced cracking (HIC) or sulfide stress cracking (SSC) are not expected in pressurized hydrogen.

Table 1: Content of Atomic Hydrogen from Different Hydrogen Sources

Charging Conditions					H concentration [ppm]
Charging Method	Duration [h]	Solution	Pressure	pH (start)	
cathodic	4	$H_2SO_4 + As_2O_3$	Voltage: -1000mV		11.2 – 15.0
chemical	48	NACE A	H_2S 1 bar	2.7	1.7 – 3.2
chemical	144	NACE A	H_2S 1 bar	2.7	1.9 – 3.3
chemical	144	EFC 16	H_2S .02 bar	3.5	0.8 – 1.6
pressurized hydrogen	720		H_2 100 bar		0.08 – 0.15

2. EUROPIPE's Hydrogen Testing Program

EUROPIPE focuses on different steel grades that were recently delivered and did not have any hydrogen related requirements. These were examined by fracture mechanical testing to demonstrate, if their toughness properties in hydrogen meet the requirements from Option B of the ASME B 31.12 code [4].

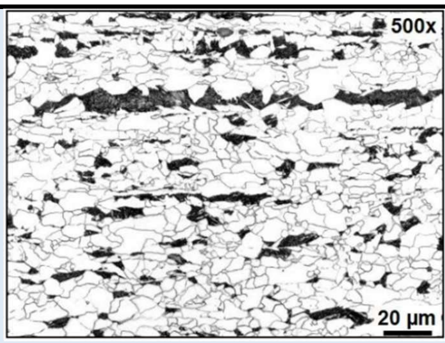
2.1. Material Characterization

For the testing, EUROPIPE selected three steels that are different from their chemical composition and their microstructure. The material was designed for a usual European onshore pipeline project in grade L485 with intermediate wall thickness (Onshore X70), for an offshore pipeline project in L485 with heavy wall (Offshore X70), and a sour service project in grade L450 with heavy wall (Sour Service X65). The three steels are introduced below.

The Onshore X70 is typical for pipes recently installed in Europe. The wall thickness of such pipes ranges up to 23 mm and these pipelines operate at pressures between 80 and 100 bars. They are optimized for meeting the requirements for gas pipelines of Annex A of ISO 3183 [5] with respect to Y/T-ratio in the tensile testing and temperature-toughness behavior in CVN-tests and DWT testing. The microstructure is ferritic-pearlitic. The chemical composition is pure CMn type, Nb-microalloyed, and with carbon contents up to 0.12 %. Ni, Cu, and Cr are not intentionally added. The carbon equivalents CE and Pcm are reaching values as high as 0.42 and 0.22 respectively. The basic data are shown in Table 2.

Table 2: Characteristics of Onshore X70

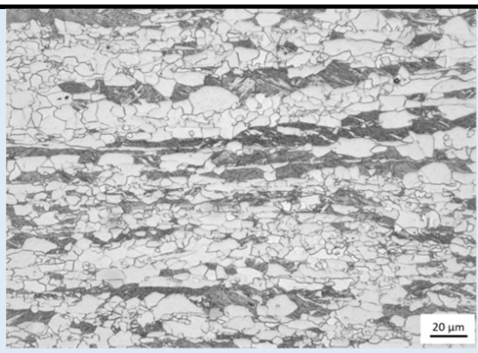
C	Mn	Si	P	S
≤0.12	1.6-1.8	≤0.45	≤0.020	≤0.002
Ni	Cu	Cr	CE	Pcm
-	-	-	≤0.42	≤0.22
$R_{t0.5}$	R_m	Y/T	A_f	
485-605	570-760	≤0.90	≥18%	



The offshore X70 concept is more dedicated to higher wall thicknesses up to 40 mm, due to high external pressures for deep-sea applications and high pressures above 200 bars. The basic technical rules are fixed in the DNV standard ST F 101 [6] and the material is optimized to meet the toughness requirements in the heat affected zone of the seam weld, which is welded with very high heat input due to the wall thickness. The microstructure is ferritic-pearlitic with a significant bainite content. The chemical composition is lower carbon CMn type, Nb-microalloyed, with Ni, Cu, and Cr additions. The carbon equivalents CE and Pcm are reaching values as high as 0.42 and 0.20 respectively. The basic data are shown in Table 3.

Table 3: Characteristics of Offshore X70

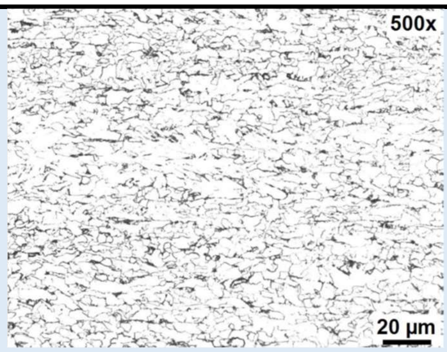
C	Mn	Si	P	S
≤0.08	1.7-1.9	≤0.30	≤0.015	≤0.002
Ni	Cu	Cr	CE	Pcm
≤0.35	≤0.30	≤0.30	≤0.42	≤0.20
$R_{t0.5}$	R_m	Y/T	A_f	
485-605	570-760	≤0.93	≥18%	



The investigation on sour service X65 is conducted to find out whether steels with high purity produced for transporting natural gas with a significant share of H_2S have a significant better mechanical performance in hydrogen than non-sour steel. Sour service is also dealing with hydrogen being absorbed in the steel, but in this case by a chemical process not by dissociation of pressurized hydrogen. The necessary high purity is achieved by measures in the steel mill like desulphurization and dephosphorization, degassing and cleanness stirring, and segregation controlled, continuous casting. All such efforts are made to reduce microstructure inhomogeneities, which might promote hydrogen induced cracking. The microstructure is ferritic-bainitic. The chemical composition is a very low carbon CMn-type, Nb-microalloyed, with additions of Ni, Cu, and Cr. The carbon equivalents CE and Pcm are reaching values up to 0.31 and 0.15 respectively. Table 4 shows the basic characteristics of this steel.

Table 4: Characteristics of Sour Service X65

C	Mn	Si	P	S
≤0.05	1.3-1.5	≤0.40	≤0.010	≤0.001
Ni	Cu	Cr	CE	Pcm
≤0.35	≤0.30	≤0.30	≤0.31	≤0.15
$R_{t0.5}$	R_m	Y/T	A_f	
485-605	570-760	≤0.93	≥18%	



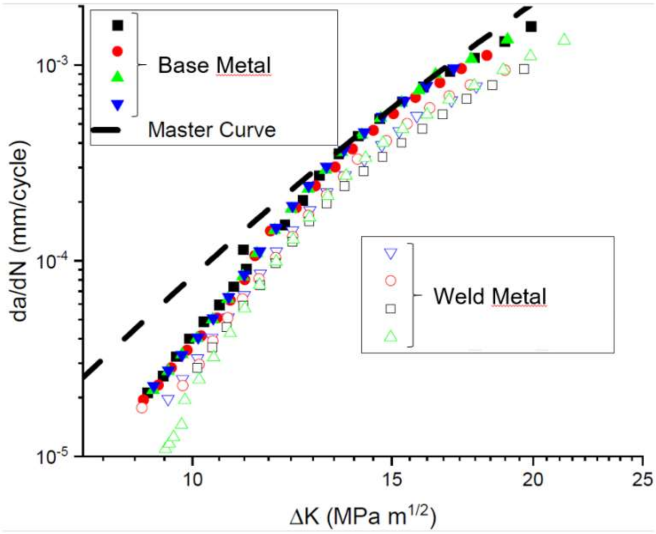
2.2. Fracture Mechanic Testing

For the design, the option B of ASME B31.12 assumes a behavior under cyclic loads fixed in a master curve following the Paris law and a minimum toughness of 55 MPa√m. The master curve parameters were determined by testing carbon steels from different production routes, different age, and different grades.

EUROPIPE's test program shall demonstrate how the three above presented steels cope with the tests in the standard, whether they meet the design assumptions or not and which steel performs better in the tests than the others. To achieve this, the material underwent cyclic testing in accordance with ASTM E647 [7] and quasi-static testing according to ASTM E1820 [8]. For the time being, only the results for the Onshore X70 is available, which are shown below. The tests were carried out at the National Institute for Standardization and Technology (NIST), in Boulder, CO, USA.

The cyclic crack propagation measurements cover a loading range for ΔK from 8 MPa√m to 20 MPa√m with the R-value 0.5. Such ΔK-values are achieved, when stress levels from 160 MPa to 400 MPa interact with the pipe with a pressure fluctuation of 50 %. The testing is performed in the base metal and the weld metal, as here the structure is more homogeneous and is not so sensitive to little differences in fatigue crack tip placement. Eight specimens are prepared and tested in an autoclave filled with pure hydrogen at a pressure of 100 bars. A test frequency of 1 Hz was selected, which is a compromise between testing practicality and worst-case scenario. Testing at lower frequencies (0.1 or 0.01 Hz) would extend testing duration significantly. Earlier investigations have shown that 1 Hz exhibits a significant difference in fatigue behavior between hydrogen atmosphere and inert environment, and the effect of lower frequencies can be re-calculated [9]. The results of the onshore grade X70 are shown in Figure 1.

Figure 1: Crack-propagation rates of base metal in 100 bar pure hydrogen for Onshore X70



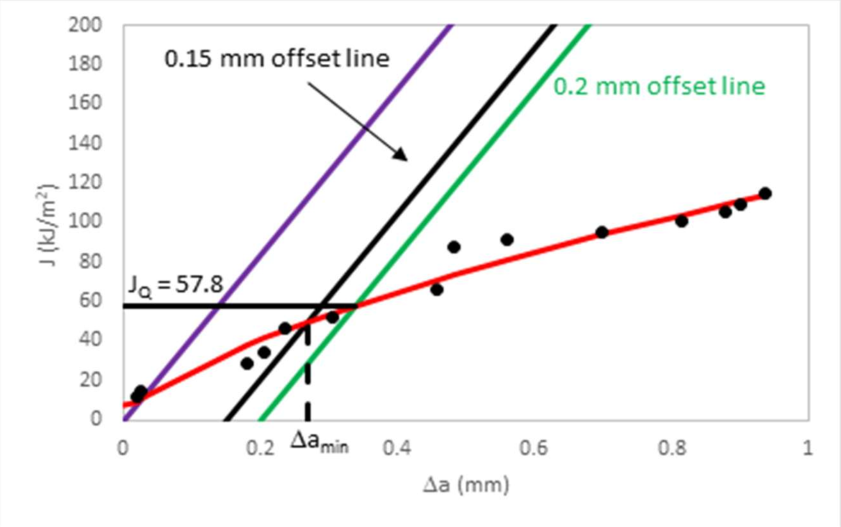
Full symbols represent the base metal tests, whereas the empty symbols are from the weld metal testing. All values line up in a very homogeneous curve in accordance with the ASME B31.12 master-curve for the crack-propagation ratio, which is drawn as the black interrupted line. The testing delivered values, which are close to this curve or fall below the assumed values.

From fracture mechanic testing in air, it is known that the heat affected zone is the lowest toughness region of the seam weld due to the high heat input from back-to-back submerged arc welding. In addition, in a real structure, flaws might develop in this zone e.g. from undercuts. Therefore, this zone was in the focus of the quasi-static fracture mechanic testing. A J-Integral based crack resistance curve in an environment of 100% hydrogen at 100 bars was developed by the partial unloading method, where crack extension is derived from constraint effects. Figure 2 displays the results of this testing and the evaluation of the critical J-value for crack initiation. The value 57.8 kJ/m² shown as J_Q represents the onset of stable crack extension under multiaxial load. It can be recalculated into a $K_{J,Ic}$ with the equation 1. The calculation results in a $K_{J,I}$-value of 114.5 MPa√m for the onset of stable crack extension, which is well above the 55 MPa√m from the ASME rules.

$$K_{J,I} = \sqrt{\frac{E\,J_I}{1-\nu^2}} \qquad \{1\}$$

$K_{J,I}$ stress intensity factor calculated from J-Integral
E Young's modulus
JI J-Integral value
v Poisson's ratio

Figure 2: Crack resistance curves of heat affected zone in 100 bar pure hydrogen for Onshore X70



The ASME BPVC Section VIII – Division 3 Article KD10 rules ASME B31.12 [10] and describes the test procedures. For the static testing, it requires testing in accordance with ASTM E1681 [11], which is designed for the determination of threshold stress intensity factors for environment-assisted cracking. The test method gives a pass/non-pass response and does not give evidence for better or worse performance. Furthermore and most important, the constant displacement test method is not applicable for the pipeline grades, as those form significant plastic zones and violate requirements from displacement measurements when uninstalling the loading bolts.

Though the constant displacement testing does not fit to pipeline material and the results does not shed too much light on hydrogen performance, EUROPIPE carried out some tests in accordance with ASME BPVC Sec. VIII – Div. 3 Art. KD10. From the order, three heats were selected and samples were taken from base metal, heat affected zone, and weld metal. Side grooves were machined to the specimens to reduce the effect of surface plain stress conditions and avoid with this the formation of large plastic zones. As no crack extension was expected, the load of 110 MPa√m was applied to the specimens; the code considers only half of the applied load when no crack extension sets in. The specimens were exposed to 100% hydrogen at 100 bars for 1,000 hours. During releasing the load, the displacement was measured. Fracture-graphic measurements result in the initial crack length to be considered for the calculation. The results are shown in Table 5.

Table 5: Results from ASTM E 1681 testing

	Heat 1			Heat 2			Heat 3		
	BM	HAZ	WM	BM	HAZ	WM	BM	HAZ	WM
K_{Iapp} [MPa√m]	115-118	118-121	112-115	116-121	121	109-116	119-125	114-122	112-117
K_{IH} [MPa√m]	58-59	59-61	56-58	58-61	61	55-58	60-63	57-61	56-59
$CMOD_{fin}$/ $CMOD_{ini}$	73-80%	75-78%	70-78%	57-77%	78-83%	77-80%	75-76%	79-81%	76-93%

The standard considers crack extension larger than 0.2mm as relevant. For the entire testing run, no value beyond this limit was detected. Therefore, the threshold value K_{IH} is half the applied value K_{Iapp}, which is constantly above the 55MPa√m from the code. ASTM E1681 requires for the constant displacement method that the final crack mouth opening displacement ($CMOD_{fin}$) shall be more 90% of the initial crack mouth opening displacement ($CMOD_{ini}$); otherwise, this method might not be suitable. Only one value out of 27 complies with this requirement. The requirement makes sense with respect to fact that pipeline steels does not fall under the linear-elastic toughness regime, as its toughness behavior is elasto-plastic also in hydrogen. The results give evidence that the testing based on ASTM E1820 is more valuable than the test procedure according to ASTM E1681.

3. Conclusions

To reduce greenhouse gases, hydrogen generation and pipelines combine perfect manner a solution for safe transport of energy from renewable electricity generation to the consumers. Therefore, it is important to know about the interactions of pressurized hydrogen with the steel pipe and the consequence a potential loss of toughness by hydrogen would have on pipeline design. ASME B31.12 defines design rules, which consider static and cyclic toughness properties of the steel grades being used in pipelines.

Coping with hydrogen pipelines is not new. Hydrogen pipelines are in operation since years, but the conservative design with pipeline grades at the lower end and pressure utilization below 50 % of SMYS gives limited experience to the plan applying an approximate pipeline design, which is current state-of-the-art for natural gas. Atomic hydrogen pick-up in pipeline steels is also known from sour service pipelines, pipelines transporting natural gas with essential portions of H_2S, but it is not clear whether the design should be transferred to pressurized hydrogen. The outcome of EUROPIPE's program is that the dissolved hydrogen content in the steel is by more than one magnitude lower in the pressurized hydrogen case than in the corrosion testing case according to NACE or EFC 16. This leads to the conclusion that sour service approaches might be not necessary.

Fracture mechanics allows a design, which considers flaws on the one hand and material toughness properties coping with such discontinuities on the other. EUROPIPE's program comprises quasi-static and cyclic fracture mechanic testing of three pipeline steel grades, an Onshore X70, an Offshore X70, and a Sour Service X65. Currently the work is not complete. The Onshore X70's first results from quasi-static testing of the heat affected zone and cyclic testing of the base metal and weld metal shows that the design according to ASME B31.12 is still safe for pipelines made of Onshore X70 steel and operated at a hydrogen partial pressure of 100 bars. Results from steels with different chemistry and microstructure about improved performance in hydrogen will follow.

For the determination of toughness properties, $K_{J,Ic}$ from the ASTM E1820 test protocol might be the better choice for pipeline material characterization than threshold testing from ASTM E1681. The validity of ASTM E1681 seems to be more linked to the linear-elastic regime and the tests violate requirements from this test standard. ASTM E1820 delivers values considering the elastic-plastic regime, which fits better to pipeline steels. Furthermore, the values can be used to compare steel performance in hydrogen.

4. References

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